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Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement--Site I

KVB, Inc.
Minneapolis, MN

Prepared for

Industrial Environmental Research Lab.
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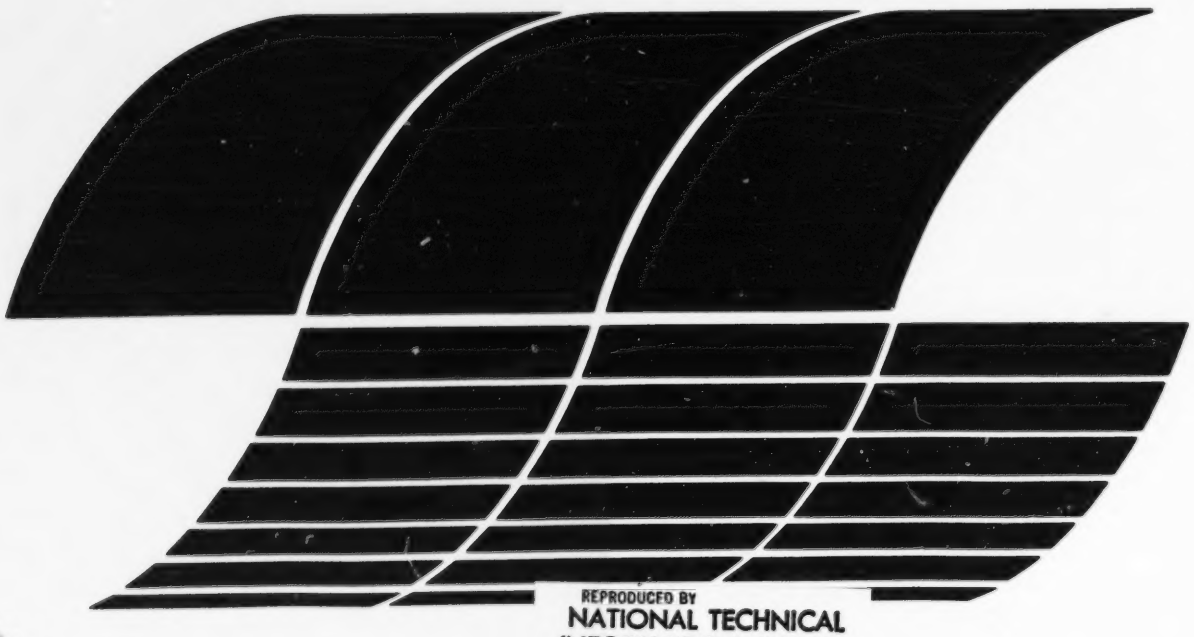

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16. ABSTRACT The report gives results of field measurements made on a 70,000 lb steam/hr coal-fired overfeed stoker with traveling grate. The effects of various parameters on boiler emissions and efficiency were studied. Parameters include overfire air, excess oxygen, grate heat release, and coal properties. Measurements include O2, CO2, NO, SO2, SO3, uncontrolled particulate loading, particle size distribution of the uncontrolled flyash, and combustible content of the ash. In addition to test results and observations, the report describes the facility tested, coals fired, test equipment, and procedures. Uncontrolled particulate loading on this unit averaged 1.2 lb/million Btu at full load. Full-load NO emissions ranged from 0.2 to 0.4 lb/million Btu.

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Coal	Fly Ash	Spreader Stokers	21D	
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E. Poitras	The McBurney Corporation
P. E. Ralston	Babcock and Wilcox
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1.0 INTRODUCTION

The principal objective of the test program described in this report, one of several reports in a series, is to produce information which will increase the ability of boiler manufacturers to design and fabricate stoker boilers that are an economical and environmentally satisfactory alternative to oil-fired units. Further objectives of the program are to: provide information to stoker boiler operators concerning the efficient operation of their boilers; provide assistance to stoker boiler operators in planning their coal supply contracts; refine application of existing pollution control equipment with special emphasis on performance; and contribute to the design of new pollution control equipment.

In order to meet these objectives, it is necessary to define stoker boiler designs which will provide efficient operation and minimum gaseous and particulate emissions, and define what those emissions are in order to facilitate preparation of attainable national emission standards for industrial size, coal-fired boilers. To do this, boiler emissions and efficiency must be measured as a function of coal analysis and sizing, rate of flyash reinjection, overfire air admission, ash handling, grate size, and other variables for different boiler, furnace, and stoker designs.

A field test program designed to address the objectives outlined above was awarded to the American Boiler Manufacturers Association (ABMA), sponsored by the United States Department of Energy (DOE) under contract number EF-77-C-01-2609, and co-sponsored by the United States Environmental Protection Agency (EPA) under inter-agency agreement number IAG-D7-E681. The program is directed by an ABMA Stoker Technical Committee which, in turn, has subcontracted the field test portion to KVB, Inc., of Minneapolis, Minnesota.

This report is the Final Technical Report for the ninth of eleven boilers to be tested under the ABMA program. It contains a description of the facility tested, the coals fired, the test equipment and procedures, and the results and observations of testing. There is also a data supplement to this report containing the "raw" data sheets from the tests conducted. The data supplement has the same EPA report number as this report except that it

is followed by "b" rather than "a". As a compilation of all data obtained at this test site, the supplement acts as a research tool for further data reduction and analysis as new areas of interest are uncovered in subsequent testing.

At the completion of this program, a Final Technical Report will combine and correlate the test results from all sites tested. A report containing operating guidelines for boiler operators will also be written, along with a separate report covering trace species data. These reports will be available to interested parties through the National Technical Information Service (NTIS) or through the EPA's Technical Library.

Although it is EPA policy to use S.I. units in all EPA sponsored reports, an exception has been made herein because English units have been conventionally used to describe boiler design and operation. Conversion tables are provided in the Appendix for those who prefer S.I. units.

To protect the interests of the host boiler facilities, each test site in this program has been given a letter designation. As the ninth site tested, this is the Final Technical Report for Test Site I under the program entitled, "A Testing Program to Update Equipment Specifications and Design Criteria for Stoker Fired Boilers."

2.0 EXECUTIVE SUMMARY

A coal fired traveling grate stoker rated at 70,000 lbs steam/hr was extensively tested for emissions and efficiency between April 29 and May 24, 1979. This section summarizes the results of these tests and provides references to supporting figures, tables and commentary found in the main text of the report.

UNIT TESTED: Described in Section 3.0, page 9.

- Wickes Boiler

  Built 1960
  Type RB
  70,000 lbs/hr rated capacity
  250 psig operating pressure
  Saturated steam

- Riley Stoker

  Overfeed stoker
  Traveling grate
  Two rows overfire air jets on front wall

COALS TESTED: Individual coal analysis given in Tables 5-9, 5-10 and 5-11, pages 54-56. Commentary in Section 3.4, page 13, and Section 5.3, page 49.

- Ohio Coal

  12,858 Btu/lb
  9.57% Ash
  2.77% Sulfur
  3.28% Moisture
  2060°F Initial ash deformation temperature

- Kentucky Coal

  13,823 Btu/lb
  6.04% Ash
  1.49% Sulfur
  2.26% Moisture
  2070°F Initial ash deformation temperature

OVERFIRE AIR TEST RESULTS: The normal operating practice on this boiler was to maintain overfire air pressure at 3-4" H_2O for all boiler loads. During three full load tests the overfire air pressure was increased to its maximum of about 10" H_2O with the following results. (Section 5.1, page 31)

0 Particulate Loading

Particulate loading dropped an average 40% when overfire pressure was increased. The percentage of combustible material in the particulate matter did not drop. (Section 5.1.1, page 31)

0 Nitric Oxide

Nitric oxide emissions increased 2 to 16% when overfire air pressure was increased. (Section 5.1.2, page 33)

0 Carbon Monoxide

No data is available. The carbon monoxide gas analyzer was out-of-service during testing at Site I.

0 Boiler Efficiency

Boiler efficiency decreased an average 2.8% when overfire air pressure was increased. The increased heat losses were bottom ash combustible losses and dry gas losses. (Section 5.1.3, page 33)

0 Overfire Air Flow Rate

Overfire air flow rate, as measured by a standard pitot tube, was shown to account for 14% of the combustion air at full load and 8% O_2. (Section 5.1.4, page 35)

BOILER EMISSION PROFILES: Boiler emissions and efficiency were measured at loads of 50%, 75% and 100% of the units design capacity. At the two higher loads, excess oxygen was varied over the range 5.0 to 10.1% O_2. Test results were as follows. (Section 5.2, page 37)

0 Excess Oxygen Operating Levels

The normal or "as-found" excess oxygen ranged from 8% O_2 at full load to nearly 12% at 50% capacity. (Section 5.2.1, page 38)

0 Particulate Loading

At full load, uncontrolled particulate loading ranged from 0.90 lb/10^6 Btu at high overfire air to 1.76 lb/10^6 Btu at low overfire air. Ash carryover averaged 11% for all tests. Particulate loading increased with increasing excess oxygen. (Section 5.2.2, page 38)

0 Nitric Oxide Emissions (NO)

At full load, nitric oxide averaged 0.31 lb/10^6 Btu burning the Ohio coal and 0.23 lb/10^6 Btu burning the Kentucky coal. The slope of NO vs O_2 was 0.014 and 0.010 lb NO/10^6 Btu respectively for the two coals. Nitric oxide concentrations decreased slightly as load increased under normal firing conditions. (Section 5.2.3, page 41)

0 Combustibles in the Ash

Flyash combustibles ranged from 22 to 37%. Bottom ash combustibles ranged from 14 to 45%. Flyash combustibles increased with load while bottom ash combustibles decreased with increasing load. (Section 5.2.4, page 46)

0 Boiler Efficiency

Boiler efficiency was highest at full load where it averaged 74.0%. The average was 73.2% at 75% capacity and 69.6% at 50% capacity. Dry gas loss was the primary factor relating boiler efficiency to load. (Section 5.2.5, page 49)

COAL PROPERTIES: Of the two coals tested, the Kentucky coal was considered a better coal than the Ohio coal because of its higher Btu content, lower sulfur, and slightly lower ash and fines. The observed effect of these coals on emissions efficiency were as follows. (Section 5.3.3, page 58)

0 Particulate Loading

Both coals produced similar particulate mass loadings. (Figure 5-4, page 40 and Table 5-13, page 58)

0 Nitric Oxide

Nitric oxide emissions were as much as 36% lower while burning Kentucky coal than while burning Ohio coal. (Table 5-14, page 59)

0 Sulfur Balance

Sulfur balance on the Kentucky coal was good with 98% of the fuel sulfur measured in the flue gas and the remaining 2% assumed retained in the ash. Sulfur balance on the Ohio coal was not as good with 30% more sulfur measured in the flue gas than measured in the coal. (Table 5-15, page 60)

- Combustibles in the Ash

  Combustibles in the flyash were invarient with coal. Combustibles in the bottom ash were less while firing Kentucky coal. (Figure 5-9 and 5-10, pages 47 and 48)

- Boiler Efficiency

  Kentucky coal averaged 3% higher boiler efficiency than did Ohio coal. Combustible heat losses account for the difference. (Table 5-16, page 61)

PARTICLE SIZE DISTRIBUTION OF FLYASH: Two particle size distribution measurements were made on the uncontrolled particulate matter in the flyash by cyclone separation at 1, 3 and 10 micrometers. These show that 24% of the sampled flyash is smaller than 10 micrometers. (Figure 5-14, page 62)

SOURCE ASSESSMENT SAMPLING SYSTEM (SASS): Flue gas was sampled for polynuclear aromatic hydrocarbons and trace elements during one full load test on each of the two coals. Data will be presented in a separate report at the completion of this test program. (Section 5.4, page 61)

The Test Outline and Emission Data Summary are presented in Tables 2-1 and 2-2 on the following pages. For reference, additional data tables are included in Section 5.6. A "Data Supplement" containing all the unreduced data obtained at Site I is available under separate cover for those who wish to further analyze the data. The "Data Supplement" has the same EPA document number as this report except that it is followed by the letter "b" rather than "a". Copies of this report and the Data Supplement are available through EPA and the National Technical Information Service (NTIS).

TABLE 2-1

TEST OUTLINE FOR TEST SITE I

FIRING CONDITIONS			TEST MEASUREMENTS BY TEST NUMBER*		
% Boiler Capacity	Excess Air	Overfire Air	Gaseous Emissions	Particulate Loading	Other Tests
100	Norm	Low	2, (15)	2, (15)	--
100	Norm	High	3, (18)	3	(18) SASS & SOx
100	Low	Low	6	--	--
100	Low	High	4, 9	4	9 SASS & SOx
100	Vary	Low	7, (16)	--	--
75	Norm	Low	5, (14)	5, (14)	--
75	Vary	Low	8	--	--
50	Norm	Low	1, (10)	1, (10)	--

*Parenthesis "( )" Around Test Numbers Indicate Kentucky Coal. In Addition to the Above Tests, Test No's 11, 12 and 13 Were For OFA Flow Rate Measurements.

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TABLE 2-2

EMISSION DATA SUMMARY
TEST SITE I

Test No.	Date	% Design Capacity	Coal*	Excess Air, %	O_2 % dry	CO_2 % dry	NO $lb/10^6$ Btu	NO ppm dry	SOx $lb/10^6$ Btu	Uncontrolled Particulate $lb/10^6$Btu
1	4/28/79	50	1	120	11.8	7.6	0.268	179	--	0.541
2	4/30/79	98	1	63	8.3	11.3	0.213	157	--	1.763
3	5/01/79	103	1	62	8.3	11.0	0.400	294	--	0.999
4	5/01/79	100	1	43	6.6	11.6	0.306	225	--	0.904
5	5/02/79	82	1	69	8.9	10.2	0.288	212	--	0.954
6	5/08/79	99	1	39	6.1	12.5	0.252	185	--	--
7a	5/09/79	104	1	50	7.2	12.1	0.324	238	--	--
7b	5/09/79	104	1	39	6.1	12.7	0.285	210	--	--
7c	5/09/79	104	1	30	5.0	13.5	0.283	208	--	--
8a	5/09/79	72	1	84	9.9	9.5	0.343	252	--	--
8b	5/09/79	72	1	66	8.6	10.8	0.330	243	--	--
8c	5/09/79	72	1	54	7.6	11.3	0.329	242	--	--
8d	5/09/79	72	1	45	6.8	11.9	0.311	229	--	--
9	5/10/79	102	1	37	5.9	12.9	0.295	217	3.656	--
10	5/12/79	48	2	116	11.6	8.0	0.326	245	--	0.734
14	5/14/79	71	2	88	10.1	9.3	0.288	213	--	1.341
15	5/22/79	101	2	54	7.6	11.7	0.236	175	--	1.430
16a	5/23/79	102	2	91	10.1	10.9	0.258	191	--	--
16b	5/23/79	102	2	68	8.7	11.5	0.243	180	--	--
16c	5/23/79	102	2	57	7.8	12.2	0.221	164	--	--
16d	5/23/79	102	2	44	6.6	13.0	0.211	156	--	--
16e	5/23/79	102	2	38	5.9	13.6	0.201	149	--	--
18	5/23/79	101	2	56	7.8	11.0	0.255	188	1.865	--

* 1 - Ohio Coal, 2 - Kentucky Coal

3.0 DESCRIPTION OF FACILITY TESTED AND COALS FIRED

This section discusses the general physical layout and operational characteristics of the boiler tested at Test Site I. The coals utilized in this test series are also discussed.

3.1 BOILER I DESCRIPTION

Boiler I is a Wickes type RB boiler, built in 1960. The boiler is designed to operate at a maximum continuous capacity of 70,000 pounds of steam per hour at 250 psig and saturated temperature. This unit has a Riley traveling grate stoker with continuous front-end discharge. Coal is brought to the boiler from the coal bunkers by a weigh lorry and is mass fed to the grate. There is no suspension burning. Undergrate air can be controlled by six zones. There is no dust collector, economizer or flyash reinjection. Design data on the boiler and stoker are presented in Table 3-1.

3.2 OVERFIRE AIR

The overfire air system on Boiler I consists of two rows of air jets on the front wall. The lower overfire air nozzles are 4-1/2 feet above the grate at a 45° angle. The upper overfire air nozzles are 6'9" above the grate, at a 30° angle below horizontal. The overfire air was found to be operating at about 3" H_2O. At maximum flow the pressure is about 10" H_2O.

3.3 TEST PORT LOCATIONS

Emission measurements were made at the stack. Because there was no dust collector, particulate measurements at this location are equivalent to boiler outlet measurements. The location of this sampling site is shown in Figure 3-1 and its geometry is shown in Figure 3-2.

Particulate measurements were made using a 24-point traverse. Gaseous measurements of O_2, CO_2, and NO were obtained by pulling samples individually

TABLE 3-1

DESIGN DATA
TEST SITE I

BOILER:	Manufacturer	Wickes Boiler Company
	Type	RB
	Boiler Heating Surface	9500 ft^2
	Design Pressure	250 psig
FURNACE:	Volume	3900 ft^3
STOKER:	Manufacturer	Riley Stoker
	Type	Traveling Grate
	Width	14'0"
	Length	18'1/2"
	Effective Grate Area	252.6 ft^2
HEAT RATES:	Steam Flow	70,000 lbs/hr
	Input to Furnace*	95 $x10^6$ Btu/hr
	Furnace Width Heat Release*	5.2 $x10^6$ Btu/hr-ft
	Grate Heat Release*	377 $x10^3$ Btu/hr-ft^2
	Furnace Liberation*	24 $x10^3$ Btu/hr-ft^3

* Heat input and heat release rates were determined by KVB based on available data and are not necessarily those of the equipment manufacturer.

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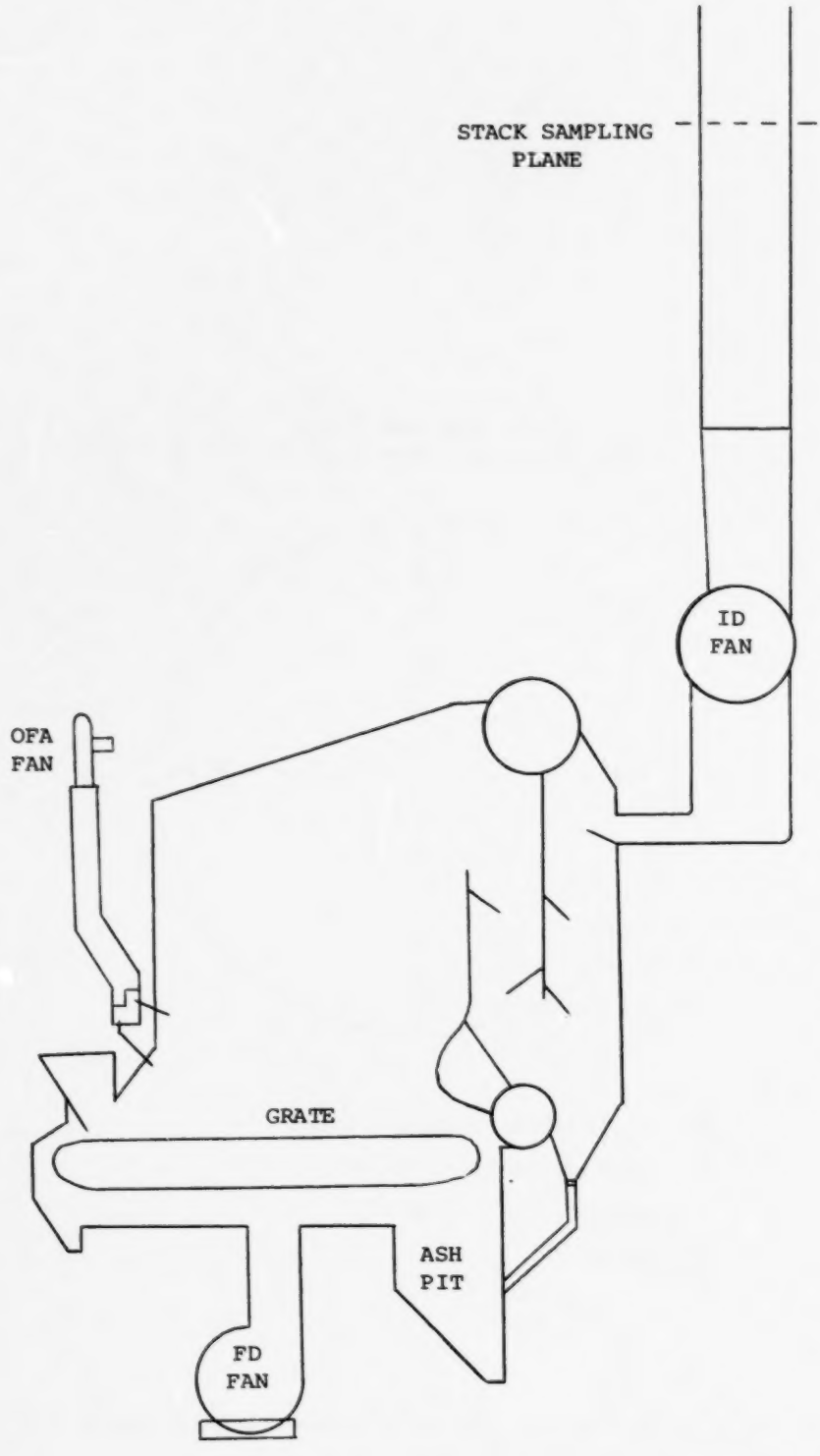

Figure 3-1. Boiler I Schematic

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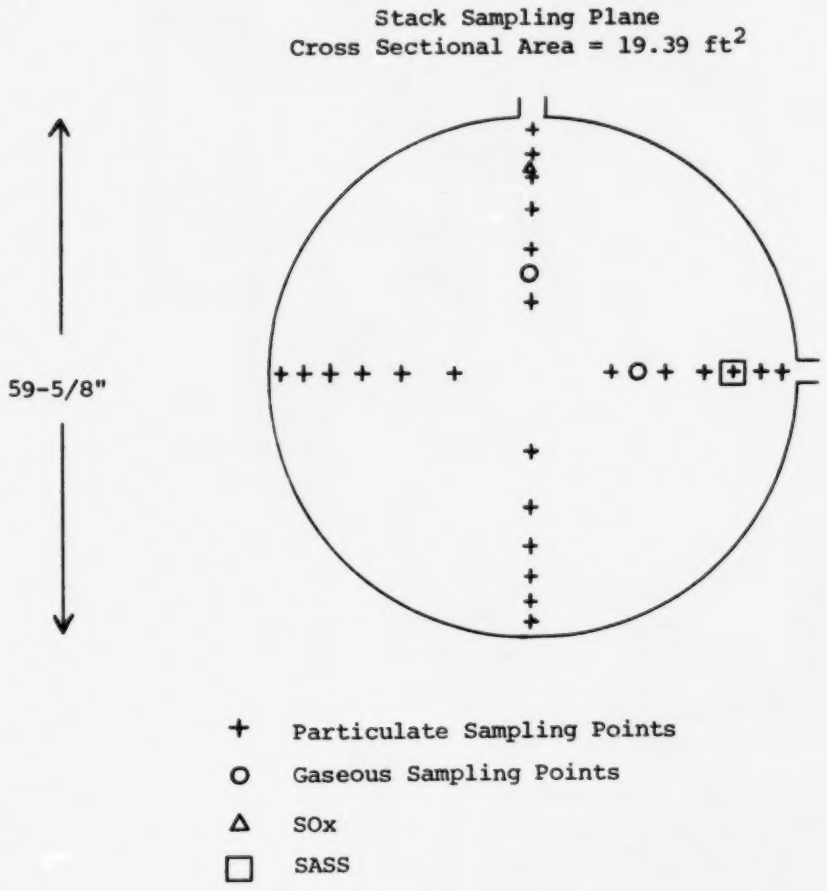

Figure 3-2. Boiler I Sample Plane Geometry

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from two probes. SOx measurements and SASS samples for organic and trace element determinations were obtained from single points within the boiler duct.

3.4 COALS UTILIZED

Two coals were test fired at Test Site I. These are referred to as Ohio coal and Kentucky coal in this report. The primary coal tested was the Ohio coal, which was supplied by C and W Mining (Columbian County, Lisbon, Ohio). The secondary coal was a higher Btu coal and it was supplied by Island Creek Coal Company. It came from the Spurlock mine in Salisbury, Kentucky.

Coal samples were taken for each test involving particulate or SASS sampling. The average coal analyses obtained from these samples are presented in Table 3-2. The analyses of each individual coal sample are presented in Section 5.0, Test Results and Observations, Tables 5-9, 5-10, and 5-11.

TABLE 3-2

AVERAGE COAL ANALYSIS
TEST SITE I

	Ohio Coal	Kentucky Coal
Proximate (As Rec'd)		
% Moisture	3.28	2.26
% Ash	9.57	6.04
% Volatile	38.02	38.79
% Fixed Carbon	49.05	52.92
Btu/lb	12,858	13,823
% Sulfur	2.77	1.49
Ultimate (As Rec'd)		
% Moisture	2.96	2.20
% Carbon	72.62	77.23
% Hydrogen	4.97	5.28
% Nitrogen	1.26	1.50
% Chlorine	0.40	0.13
% Sulfur	1.88	1.38
% Ash	8.37	5.34
% Oxygen (diff)	7.54	6.93

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4.0 TEST EQUIPMENT AND PROCEDURES

This section details how specific emissions were measured and the sampling procedures followed to assure that accurate, reliable data were collected. Note that the carbon monoxide monitor was out-of-service during testing on this unit.

4.1 GASEOUS EMISSIONS MEASUREMENTS (NOx, CO, CO_2, O_2, HC)

A description is given below of the analytical instrumentation, related equipment, and the gas sampling and conditioning system, all of which are located in a mobile testing van owned and operated by KVB. The systems have been developed as a result of testing since 1970, and are operational and fully checked out.

4.1.1 Analytical Instruments and Related Equipment

The analytical system consists of five instruments and associated equipment for simultaneously measuring the constituents of flue gas. The analyzers, recorders, valves, controls, and manifolds are mounted on a panel in the vehicle. The analyzers are shock mounted to prevent vibration damage. The flue gas constituents which are measured are oxides of nitrogen (NO, NOx), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and gaseous hydrocarbons (HC).

Listed below are the measurement parameters, the analyzer model furnished, and the range and accuracy of each parameter for the system. A detailed discussion of each analyzer follows:

Constituent:	Nitric Oxide/Total Oxides of Nitrogen (NO/NOx)
Analyzer:	Thermo Electron Model 10 Chemiluminescent Analyzer
Range:	0-2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm NO
Accuracy:	±1% of full scale

Constituent:	Carbon Monoxide
Analyzer:	Beckman Model 315B NDIR Analyzer
Range:	0-500 and 0-2000 ppm CO
Accuracy:	±1% of full scale

Constituent:	Carbon Dioxide
Analyzer:	Beckman Model 864 NDIR Analyzer
Range:	0-5% and 0-20% CO_2
Accuracy:	±1% of full scale

Constituent:	Oxygen
Analyzer:	Teledyne Model 326A Fuel Cell Analyzer
Range:	0-5, 10, and 25% O_2 full scale
Accuracy:	±1% of full scale

Constituent:	Hydrocarbons
Analyzer:	Beckman Model 402 Flame Ionization Analyzer
Range:	5 ppm full scale to 10% full scale
Accuracy:	±1% of full scale

Oxides of nitrogen. The instrument used to monitor oxides of nitrogen is a Thermo Electron chemiluminescent nitric oxide analyzer. The instrument operates by measuring the chemiluminescent reaction of NO and O_3 to form NO_2. Light is emitted when electronically excited NO_2 molecules revert to their ground state. The resulting chemiluminescence is monitored through an optical filter by a high sensitivity photomultiplier, the output of which is linearly proportional to the NO concentration.

Air for the ozonator is drawn from ambient air through a dryer and a ten micrometer filter element. Flow control for the instrument is accomplished by means of a small bellows pump mounted on the vent of the instrument downstream of a separator that prevents water from collecting in the pump.

The basic analyzer is sensitive only to NO molecules. To measure NOx (i.e., $NO+NO_2$), the NO_2 is first converted to NO. This is accomplished by a converter which is included with the analyzer. The conversion occurs as the gas passes through a thermally insulated, resistance heated, stainless steel coil. With the application of heat, NO_2 molecules in the sample gas are reduced to NO molecules, and the analyzer now reads NOx. NO_2 is obtained by the difference in readings obtained with and without the converter in operation.

Specifications:
- Accuracy 1% of full scale
- Span stability ±1% of full scale in 24 hours
- Zero stability ±1 ppm in 24 hours
- Power requirements 115±10V, 60 Hz, 1000 watts
- Response 90% of full scale in 1 sec. (NOx mode), 0.7 sec. NO mode
- Output 4-20 ma

Sensitivity 0.5 ppm
Linearity ±1% of full scale
Vacuum detector operation
Range: 2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm full scale

Carbon Monoxide. Carbon monoxide concentration is measured by a Beckman 315B non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the CO analyzer are 0-500 ppm and 0-2000 ppm.

Specifications:
Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma

Carbon Dioxide. Carbon dioxide concentration is measured by a Beckman Model 864 short path-length, non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the CO_2 analyzer are 0-5% and 0-20%.

Specifications:
Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma

Oxygen. The oxygen content of the flue gas sample is automatically and continuously determined with a Teledyne Model 326A Oxygen analyzer. Oxygen in the flue gas diffuses through a Teflon membrane and is reduced on the surface of the cathode. A corresponding oxidation occurs at the anode internally and an electric current is produced that is proportional to the concentration of oxygen. This current is measured and conditioned by the instrument's electronic circuitry to give a final output in percent O_2 by volume for operating ranges of 0% to 5%, 0% to 10%, or 0% to 25%.

Specifications:
- Precision ±1% of full scale
- Response 90% in less than 40 sec.
- Sensitivity 1% of low range
- Linearity ±1% of full scale
- Ambient temperature range 32-125°F
- Fuel cell life expectancy 40,000%-hours
- Power requirement 115 VAC, 50-60 Hz, 100 watts
- Output 4-20 ma

Hydrocarbons. Hydrocarbons are measured using a Beckman Model 402 hydrocarbon analyzer which utilizes the flame ionization method of detection. The sample is drawn to the analyzer through a heated line to prevent the loss of higher molecular weight hydrocarbons. It is then filtered and supplied to the burner by means of a pump and flow control system. The sensor, which is the burner, has its flame sustained by regulated flows of fuel (40% hydrogen plus 60% helium) and air. In the flame, the hydrocarbon components of the sample undergo a complete ionization that produces electrons and positive ions. Polarized electrodes collect these ions, causing a small current to flow through a circuit. This ionization current is proportional to the concentration of hydrocarbon atoms which enter the burner. The instrument is available with range selection from 5 ppm to 10% full scale as CH_4.

Specifications:
- Full scale sensitivity, adjustable from 5 ppm CH_4 to 10% CH_4
- Ranges: Range multiplier switch has 8 positions: X1, X5, X10, X50, X100, X500, X1000, and X5000. In addit n, span control provides continuously variable adjustment within a dynamic range of 10:1
- Response time 90% full scale in 0.5 sec.
- Precision ±1% of full scale
- Electronic stability ±1% of full scale for successive identical samples

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Reproducibility ±1% of full scale for successive identical samples
Analysis temperature: ambient
Ambient temperature 32°F to 110°F
Output 4-20 ma
Air requirements 350 to 400 cc/min of clean, hydrocarbon-free air, supplied at 30 to 200 psig
Fuel gas requirements 75 to 80 cc/min of pre-mixed fuel consisting of 40% hydrogen and 60% nitrogen or helium, supplied at 30 to 200 psig
Electrical power requirements 120V, 60 Hz
Automatic flame-out indication and fuel shut-off valve

4.1.2 Recording Instruments

The output of the four analyzers is displayed on front panel meters and are simultaneously recorded on a Texas Instrument Model FLO4W6D four-pen strip chart recorder. The recorder specifications are as follows:

Chart size 9-3/4 inch
Accuracy ±0.25%
Linearity <0.1%
Line voltage 120V±10% at 60 Hz
Span step response: one second

4.1.3 Gas Sampling and Conditioning System

The gas sampling and conditioning system consists of probes, sample lines, valves, pumps, filters and other components necessary to deliver a representative, conditioned sample gas to the analytical instrumentation. The following sections describe the system and its components. The entire gas sampling and conditioning system shown schematically in Figure 4-1 is contained in the emission test vehicle.

4.1.4 Gaseous Emission Sampling Techniques

Boiler access points for gaseous sampling are selected in the same sample plane as are particulate sample points. Each probe consists of one-half inch 316 stainless steel heavy wall tubing. A 100 micrometer Mott Metallurgical Corporation sintered stainless steel filter is attached to each probe for removal of particulate material.

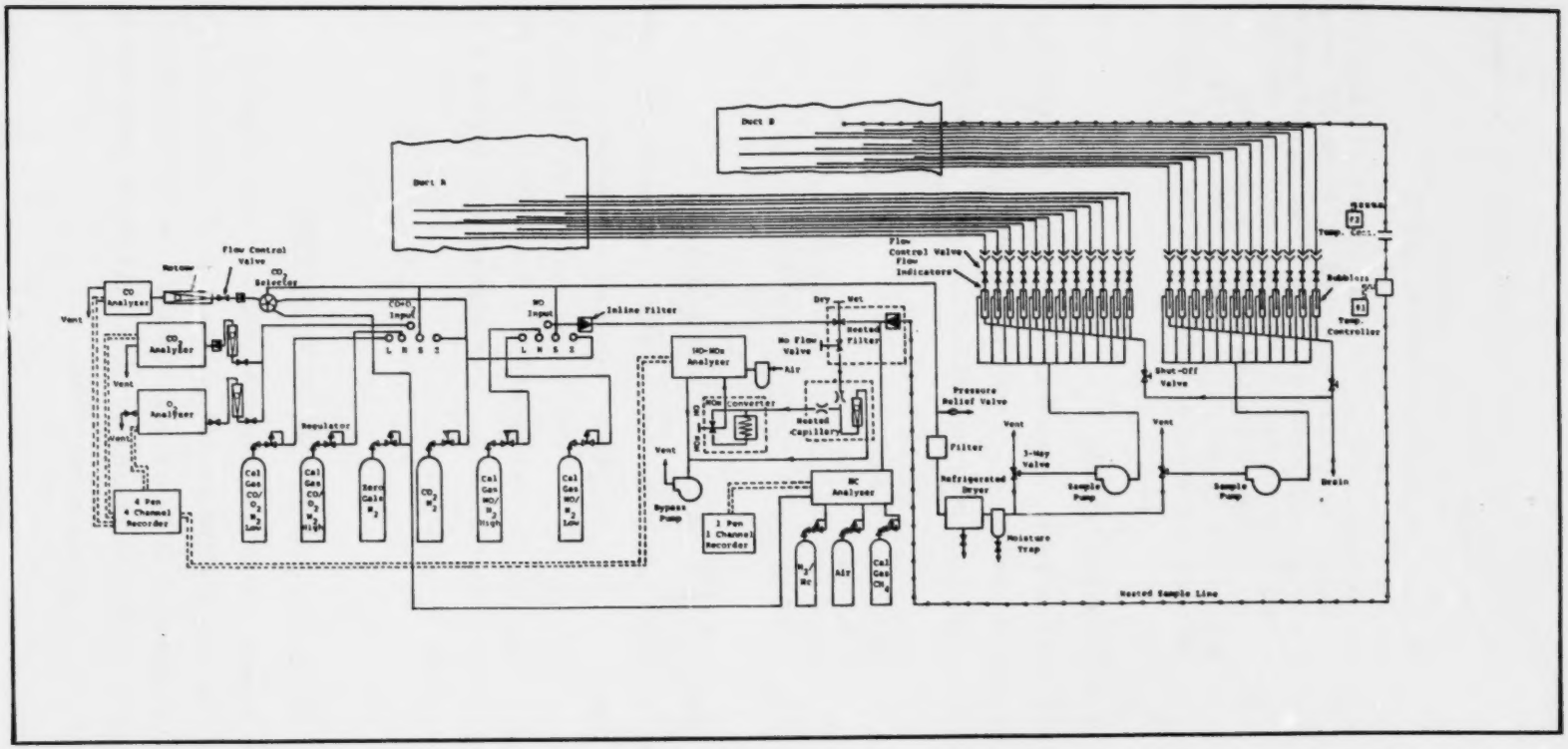

Figure 4-1. Flow Schematic of Mobile Flue Gas Monitoring Laboratory

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Gas samples to be analyzed for O_2, CO_2, CO and NO are conveyed to the KVB mobile laboratory through 3/8 inch nylon sample lines. After passing through bubblers for flow control, the samples pass through a diaphragm pump and a refrigerated dryer to reduce the sample dew point temperature to 35°F. After the dryer, the sample gas is split between the various continuous gas monitors for analysis. Flow through each continuous monitor is accurately controlled with rotometers. Excess flow is vented to the outside. Gas samples may be drawn both individually and/or compositely from all probes during each test. The average emission values are reported in this report.

4.2 SULFUR OXIDES (SOx) MEASUREMENT AND PROCEDURES

Measurement of SO_2 and SO_3 concentrations is made by wet chemical analysis using both the "Shell-Emeryville" method and EPA Method 6. In the Shell-Emeryville method the gas sample is drawn from the stack through a glass probe (Figure 4-2), containing a quartz wool filter to remove particulate matter, into a system of three sintered glass plate absorbers (Figure 4-3). The first two absorbers contain aqueous isopropyl alcohol and remove the sulfur trioxide; the third contains aqueous hydrogen peroxide solution which absorbs the sulfur dioxide. Some of the sulfur trioxide is removed by the first absorber, while the remainder, which passes through as sulfuric acid mist, is completely removed by the secondary absorber mounted above the first. After the gas sample has passed through the absorbers, the gas train is purged with nitrogen to transfer sulfur dioxide, which has dissolved in the first two absorbers, to the third absorber to complete the separation of the two components. The isopropyl alcohol is used to inhibit the oxidation of sulfur dioxide to sulfur trioxide before it gets to the third absorber.

The isopropyl alcohol absorber solutions are combined and the sulfate resulting from the sulfur trioxide absorption is titrated with standard lead perchlorate solution using Sulfonazo III indicator. In a similar manner, the hydrogen peroxide solution is titrated for the sulfate resulting from the sulfur dioxide absorption.

The gas sample is drawn from the flue by a single probe made of quartz glass inserted into the duct approximately one-third to one-half way.

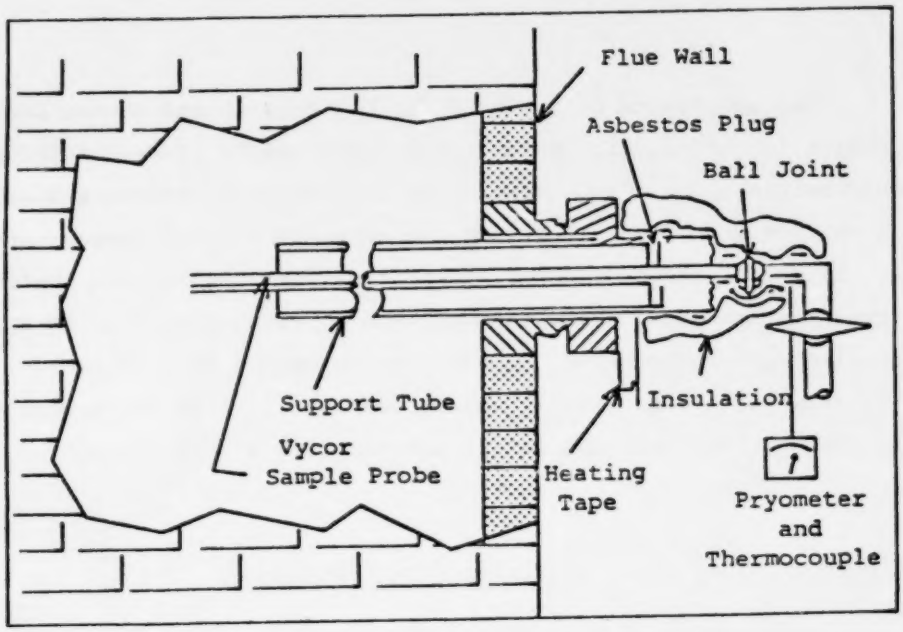

Figure 4-2. SOx Sample Probe Construction

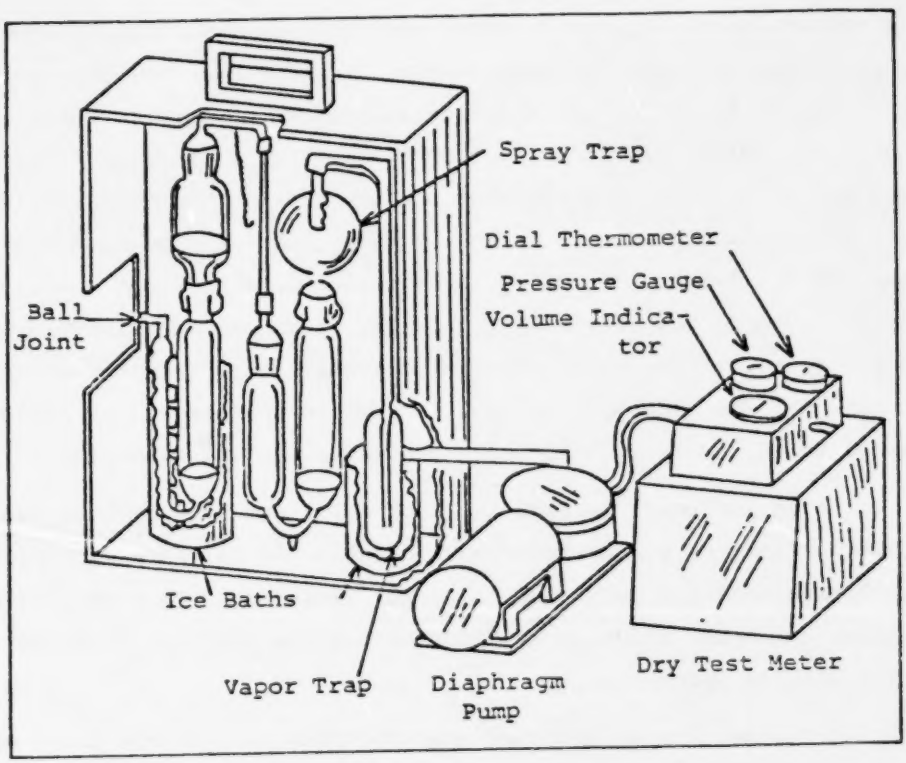

Figure 4-3. Sulfur Oxides Sampling Train
(Shell-Emeryville)

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The inlet end of the probe holds a quartz wool filter to remove particulate matter. It is important that the entire probe temperature be kept above the dew point of sulfuric acid during sampling (minimum temperature of 260°C). This is accomplished by wrapping the probe with a heating tape.

EPA Method 6, which is an alternative method for determining SO_2 (Figure 4-4), employs an impinger train consisting of a bubbler and three midget impingers. The bubbler contains isopropanol. The first and second impingers contain aqueous hydrogen peroxide. The third impinger is left dry. The quartz probe and filter used in the Shell-Emeryville method is also used in Method 6.

Method 6 differs from Shell-Emeryville in that Method 6 requires that the sample rate be proportional to stack gas velocity. Method 6 also differs from Shell-Emeryville in that the sample train in Method 6 is purged with ambient air, instead of nitrogen. Sample recovery involves combining the solutions from the first and second impingers. A 10 ml aliquot of this solution is then titrated with standardized barium perchlorate.

Two repetitions of Shell-Emeryville and two repetitions of EPA Method 6 were made during each test.

4.3 PARTICULATE MEASUREMENT AND PROCEDURES

Particulate samples are taken at the same sample ports as the gaseous emission samples using a Joy Manufacturing Company portable effluent sampler (Figure 4-5). This system, which meets the EPA design specifications for Test Method 5, Determination of Particulate Emissions from Stationary Sources (Federal Register, Volume 36, No. 27, page 24888, December 23, 1971), is used to perform both the initial velocity traverse and the particulate sample collection. Dry particulates are collected in a heated case using first a cyclone to separate particles larger than five micrometers and a 100 mm glass fiber filter for retention of particles down to 0.3 micrometers. Condensible particulates are collected in a train of four Greenburg-Smith impingers in an ice water bath. The control unit includes a total gas meter and thermocouple indicator. A pitot tube system is provided for setting sample flows to obtain isokinetic sampling conditions.

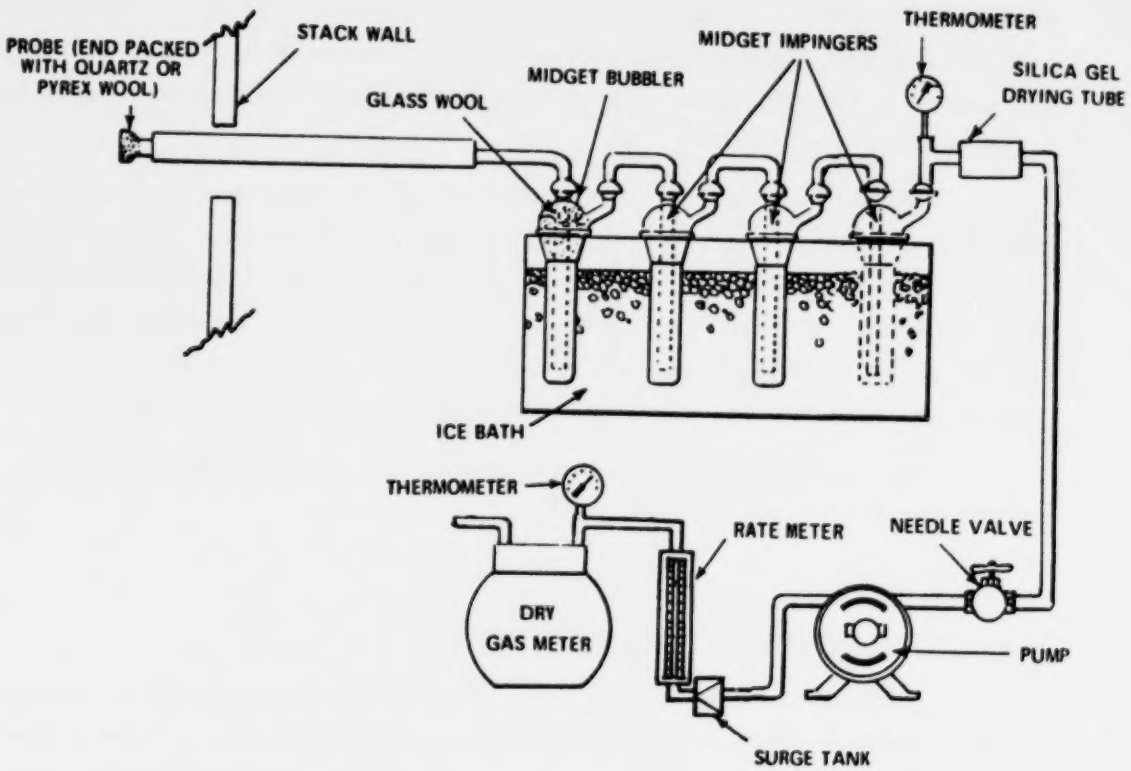

Figure 4-4. EPA Method 6 Sulfur Oxide Sampling Train

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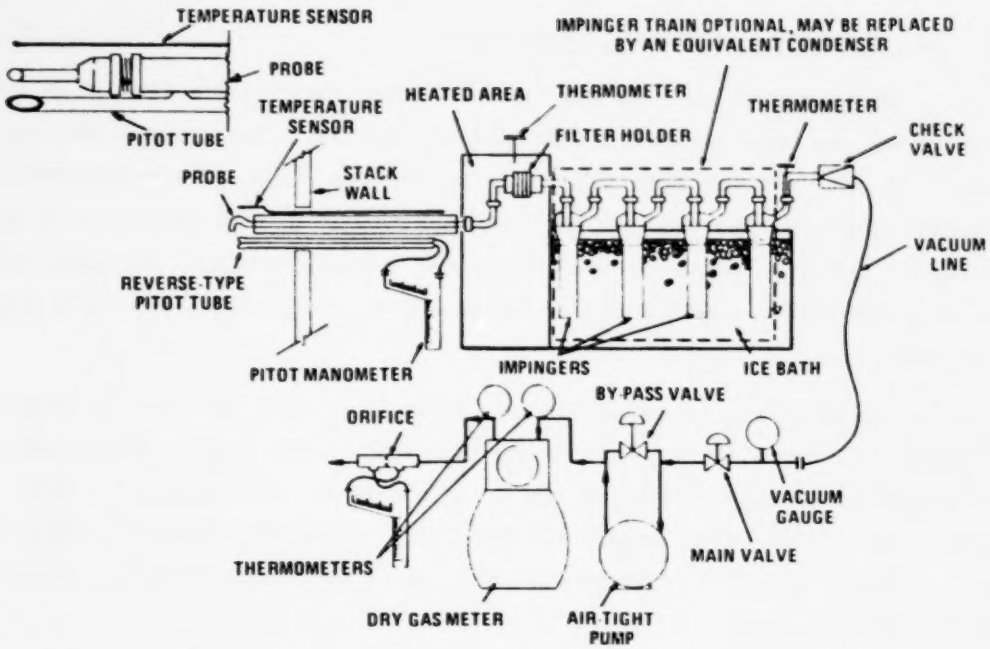

Figure 4-5. EPA Method 5 Particulate Sampling Train

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All peripheral equipment is carried in the instrument van. This includes a scale (accurate to ±0.1 mg), hot plate, drying oven (212°F), high temperature oven, desiccator, and related glassware. A particulate analysis laboratory is set up in the vicinity of the boiler in a vibration-free area. Here filters are prepared, tare weighed and weighed again after particulate collection. Also, probe washes are evaporated and weighed in the lab.

4.4 COAL SAMPLING AND ANALYSIS PROCEDURE

Coal samples at Test Site I were taken during each test from the weigh lorry, as coal was being added to the boiler. The samples were processed and analyzed for both size consistency and chemical composition. This is close enough to the furnace that the coal sampled simultaneously with testing is representative of the coal fired during testing. In order to collect representative coal samples, ten pounds of coal were taken from each batch added from the weigh lorry.

The sampling procedure is as follows. At the start of testing one increment of sample is collected from the weigh lorry. This is repeated for each batch of coal added during the test (three to five hours duration) so that a 7 to 12 increment sample is obtained. The total sample is then riffled using a Gilson Model SP-2 Porta Splitter until two representative twenty-point samples are obtained.

The sample to be used for sieve analysis is air dried overnight. Drying of the coal is necessary for good separation of fines. If the coal is wet, fines cling to the larger pieces of coal and to each other. Once dry, the coal is sized using a six tray Gilson Model PS-3 Porta Screen. Screen sizes used are 1", 1/2", 1/4", #8 and #16 mesh. Screen area per tray is 14"x14". The coal in each tray is weighed on a triple beam balance to the nearest 0.1 gram.

The coal sample for chemical analysis is reduced to 2-3 pounds by further riffling and sealed in a plastic bag. All coal samples are sent to Commercial Testing and Engineering Company, South Holland, Illinois. Each sample associated with a particulate loading or particle sizing test is given

a proximate analysis. In addition, composite samples consisting of one increment of coal for each test for each coal type receive ultimate analysis, ash fusion temperature, mineral analysis, Hardgrove grindability and free swelling index measurements.

4.5 ASH COLLECTION AND ANALYSIS FOR COMBUSTIBLES

The combustible content of flyash is determined in the field by KVB in accordance with ASTM D3173, "Moisture in the Analysis Sample of Coal and Coke" and ASTM D3174, "Ash in the Analysis Sample of Coal and Coke."

The flyash sample is collected by the EPA Method 5 particulate sample train while sampling for particulates. The cyclone catch is placed in a desiccated and tare-weighed ceramic crucible. The crucible with sample is heated in an oven at 230°F to remove its moisture. It is then desiccated to room temperature and weighed. The crucible with sample is then placed in an electric muffle furnace maintained at a temperature of 1400°F until ignition is complete and the sample has reached a constant weight. It is cooled in a desiccator over desiccant and weighed. Combustible content is calculated as the percent weight loss of the sample based on its post 230°F weight.

At Test Site I the bottom ash samples were collected in several increments from the ash pit after testing. These samples were mixed, quartered, and sent to Commercial Testing and Engineering Company for combustible determination.

4.6 BOILER EFFICIENCY EVALUATION

Boiler efficiency is calculated using the ASME Test Form for Abbreviated Efficiency Test, Revised, September, 1965. The general approach to efficiency evaluation is based on the assessment of combustion losses. These losses can be grouped into three major categories: stack gas losses, combustible losses, and radiation losses. The first two groups of losses are measured directly. The third is estimated from the ABMA Standard Radiation Loss Chart.

Unlike the ASME test in which combustible losses are lumped into one category, combustible losses are calculated and reported separately for combustibles in the bottom ash and combustibles in the flyash leaving the boiler.

4.7 TRACE SPECIES MEASUREMENT

The EPA (IERL-RTP) has developed the Source Assessment Sampling System (SASS) train for the collection of particulate and volatile matter in addition to gaseous samples (Figure 4-6). The "catch" from the SASS train is analyzed for polynuclear aromatic hydrocarbons (PAH) and inorganic trace elements.

In this system, a stainless steel heated probe is connected to an oven module containing three cyclones and a filter. Size fractionation is accomplished in the series cyclone portion of the SASS train, which incorporates the cyclones in series to provide large quantities of particulate matter which are classified by size into three ranges:

A) >10 μm B) 3 μm to 10 μm C) 1 μm to 3 μm

Together with a filter, a fourth cut (<1 μm) is obtained. Volatile organic material is collected in an XAD-2 sorbent trap. The XAD-2 trap is an integral part of the gas treatment system which follows the oven containing the cyclone system. The gas treatment system is composed of four primary components: the gas conditioner, the XAD-2 organic sorbent trap, the aqueous condensate collector, and a temperature controller. The XAD-2 sorbent is a porous polymer resin with the capability of absorbing a broad range of organic species. Some trapping of volatile inorganic species is also anticipated as a result of simple impaction. Volatile inorganic elements are collected in a series of impingers. The pumping capacity is supplied by two 10 cfm high volume vacuum pumps, while required pressure, temperature, power and flow conditions are obtained from a main controller.

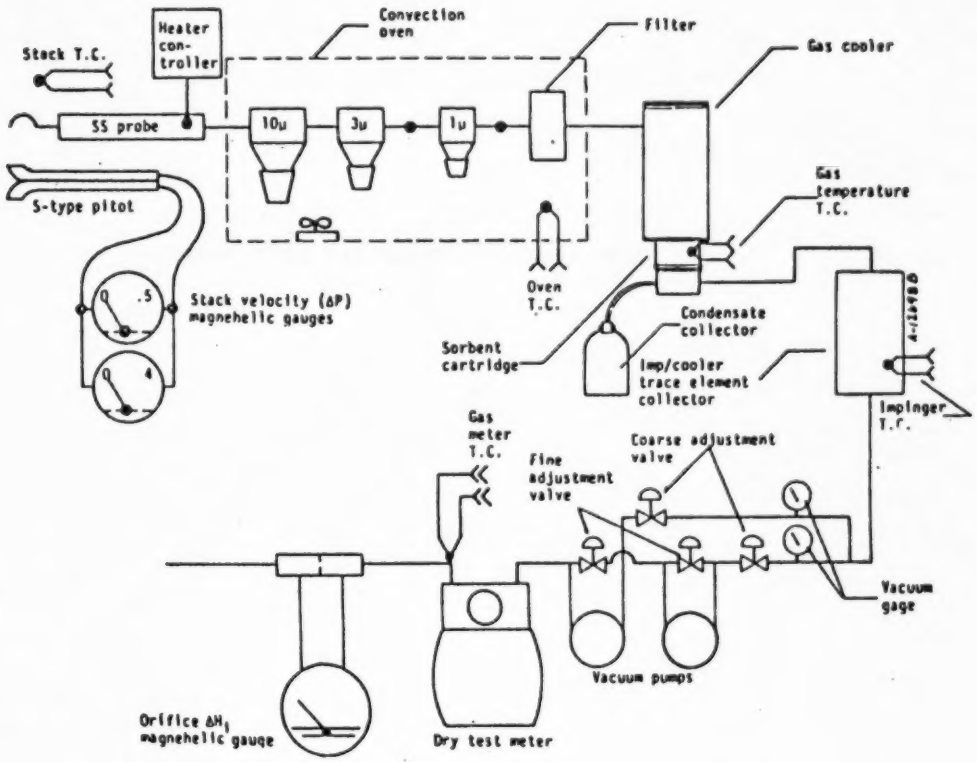

Figure 4-6. Source Assessment Sampling System (SASS) Sampling Train

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5.0 TEST RESULTS AND OBSERVATIONS

This section of the report presents the results of tests performed on Boiler I. Observations are made regarding the influence on gaseous and particulate emissions and on boiler efficiency as the control parameters were varied. Reference may be made to the Emission Data Summary, Table 2-2, in the Executive Summary, and to Tables 5-18 through 5-21 at the end of this section when reading the following discussions.

5.1 OVERFIRE AIR

The overfire air system on Boiler I consisted of two rows of air jets on the front water wall. Air flow to these jets could be manually controlled up to a maximum of about eleven inches water pressure. However, normal operating procedure at this site was to maintain overfire air flow at 3-4" H_2O for all boiler loads.

In order to investigate the effect of overfire air on emissions and efficiency, the OFA was increased to 8-11" H_2O during four tests at full load. The test data, presented in Table 5-1, indicate that increased overfire air reduced the particulate mass loading, increased nitric oxide emissions slightly, and reduced boiler efficiency. Each of these results are discussed further in the following paragraphs.

Tests were also run to determine the amount of combustion air supplied by the overfire air system, and to relate overfire air flow rate to static pressure in the overfire air duct. These tests indicate that overfire air supplies 14% of the combustion air on Boiler I at full load, 8% O_2 and 11" H_2O overfire air pressure.

5.1.1 Particulate Loading vs Overfire Air

Particulate mass loading dropped when overfire air pressure was increased from an average of 3.6 to an average of 10.7" H_2O. The mechanism for this particulate reduction can be partially attributed to improved flyash burnout as seen in the two directly comparable tests, No's. 2 and 3. In these tests the high overfire air, Test No. 3, resulted in a 43% decrease in particulate

TABLE 5-1

EFFECT OF OVERFIRE AIR ON EMISSIONS AND EFFICIENCY
TEST SITE I

TEST NO.	SET I		SET II		SET III	
	2	3	6	4	15	18
Description	Low OFA Norm O_2	High OFA Norm O_2	Low OFA Low O_2	High OFA Low O_2	Low OFA Norm O_2	High OFA Norm O_2
FIRING CONDITIONS						
Load, % of Capacity	98	103	99	100	101	101
Grate Heat Release, 10^3Btu/hr-ft^2	414	436	415	422	423	430
Coal	Ohio	Ohio	Ohio	Ohio	Ky	Ky
Coal Fines, % Passing 1/4"	37	22	25	24	30	11
Excess Air, %	63	62	39	43	54	56
Overfire Air Static Press., "H_2O	3.2	10.5	3.0	10.8	4.0	8.0
UNCONTROLLED EMISSIONS						
Particulate Loading, lb/10^6Btu	1.76	1.00	--	0.90	1.43	--
Combustible Loading, lb/10^6Btu	0.65	0.22	--	0.23	--	--
Inorganic Ash Loading, lb/10^6Btu	1.12	0.78	--	0.67	--	--
Combustibles in Flyash, %	36.7	22.0	--	25.6	--	--
Combustibles in Bottom Ash, %	24.3	35.9	--	--	14.1	18.4
O_2, % (dry)	8.3	8.3	6.1	6.6	7.6	7.8
CO_2, % (dry)	11.3	11.0	12.5	11.6	11.7	11.0
NO, lb/10^6Btu	--	0.400	0.252	0.306	0.236	0.255
HEAT LOSSES, %						
Dry Gas	15.90	16.73	13.11	15.20	14.84	17.49
Moisture in Fuel	0.39	0.34	0.26	0.36	0.24	0.19
H_2O from Combustion of H_2	4.57	4.59	4.37	4.61	4.45	4.51
Combustibles in Flyash	0.92	0.31	0.39	0.33	0.57	0.61
Combustibles in Bottom Ash	2.72	5.05	4.80	5.57	0.81	0.92
Radiation	0.55	0.52	0.55	0.54	0.54	0.53
Unmeasured	1.50	1.50	1.50	1.50	1.50	1.50
Total Losses	26.55	29.04	24.98	28.11	22.95	25.75
Boiler Efficiency	73.45	70.96	75.02	71.89	77.05	74.25

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loading. Slightly over one-half of this decrease can be attributed to improved flyash burnout. The two tests were run with identical total air flows. Therefore, Test No. 3, the one with higher overfire air, had a slightly lower air flow through the grate. This lower grate air flow, about 7% lower, may also have contributed to the particulate reduction. The data are summarized in Table 5-2 and presented graphically in Figure 5-4 of Section 5.2.

TABLE 5-2

PARTICULATE LOADING VS OVERFIRE AIR

Test No.	Overfire Air "H_2O	Uncontrolled Particulate Loading $lb/10^6$ Btu
2	3.2 (Norm)	1.76
15	4.0 (Norm)	1.43
3	10.3 (High)	1.00
4	10.8 (High)	0.90

5.1.2 Nitric Oxide vs Overfire Air

The nitric oxide (NO) concentration increased slightly when overfire air pressure was increased. This relationship between NO concentration and OFA is shown in Figure 5-1. When data from each of the two coals are examined separately, the high overfire air NO concentrations are shown to be greater than the low overfire air concentrations by 2 to 16% at the same oxygen levels.

5.1.3 Boiler Efficiency vs Overfire Air

Boiler efficiency decreased an average 2.8% when overfire air pressure was increased. The effect of overfire air on the pertinent heat loss categories is summarized in Table 5-3. For complete heat loss data refer back to Table 5-1.

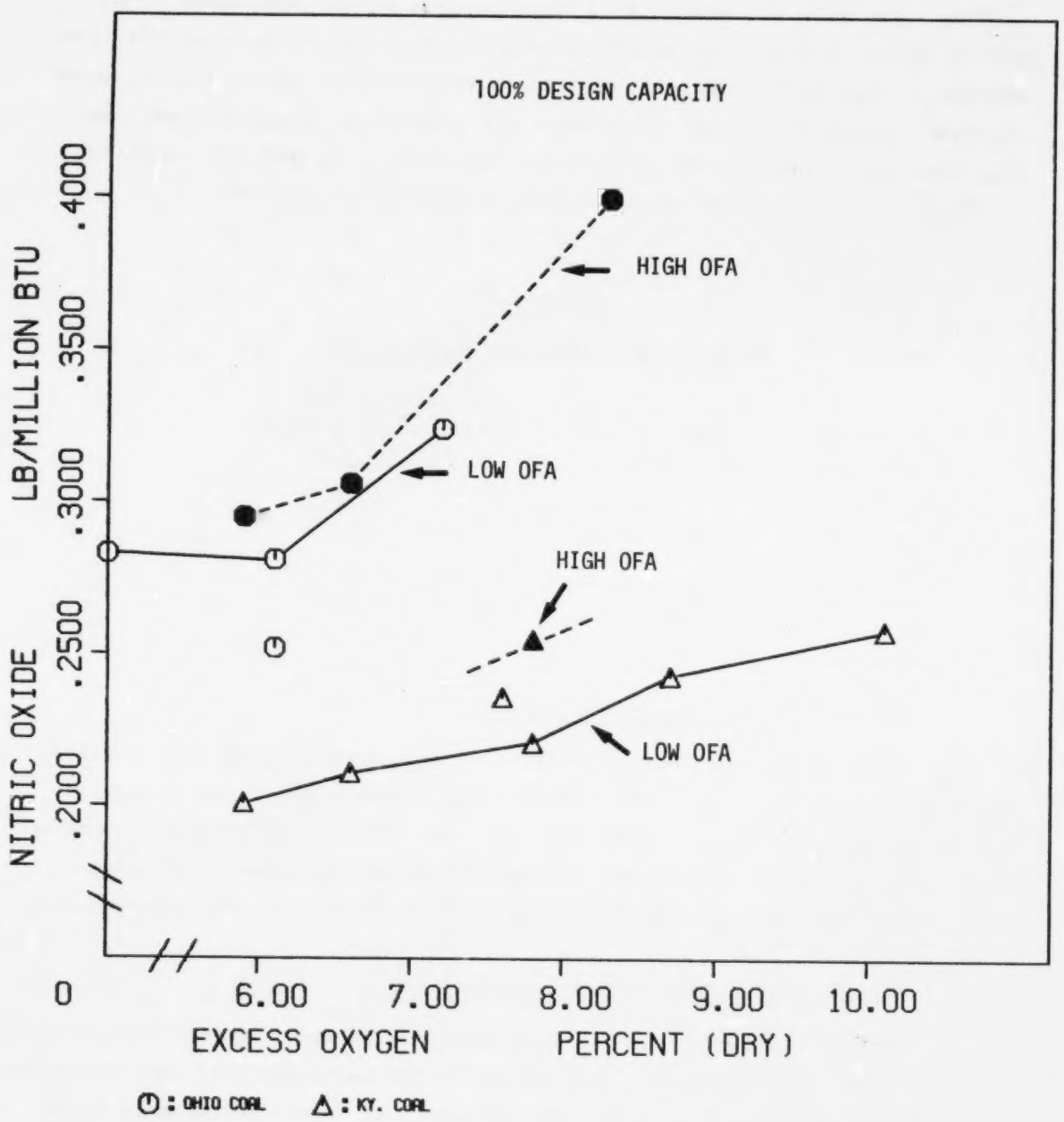

FIG. 5-1

NITRIC OXIDE VS. EXCESS OXYGEN
TEST SITE I

LINES CONNECT THOSE DATA POINTS FOR WHICH EXCESS OXYGEN IS THE ONLY KNOWN VARIABLE, AND WHICH WERE OBTAINED SUCCESSFULLY ON THE SAME DAY.

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TABLE 5-3

BOILER EFFICIENCY VS OVERFIRE AIR

	SELECTED HEAT LOSSES, %			BOILER EFFICIENCY %
	Dry Gas	Flyash Combustibles	Bottom Ash Combustibles	
Low OFA (avg of tests 2, 6, 15)	14.62	0.63	2.78	75.17
High OFA (avg of tests 3, 4, 18)	16.47	0.42	3.85	72.37
Heat Loss Difference	+1.85	-0.21	+1.07	-2.81

Table 5-3 indicates that increasing the overfire air pressure also increases the dry gas heat loss. This occurs despite a relatively constant excess air which averages 52% for the three low OFA tests and 54% for the three high OFA tests. Also evident is a decrease in heat loss due to combustibles in the flyash, and an increase in heat loss due to combustibles in the bottom ash. The increased dry gas and bottom ash combustible heat losses override the small flyash combustible heat gain resulting in the 2.8% efficiency loss due to increased overfire air.

For a graphical presentation of the flyash combustible, bottom ash combustible and boiler efficiency data, and the effect of overfire air change on this data, look ahead to Figures 5-9, 5-10 and 5-11 in Section 5.2.

5.1.4 Overfire Air Flow Rate

The rate at which air is injected into the furnace above the grate was measured using a standard pitot tube traverse of the overfire air duct. These measurements were made at three overfire air settings of 3.5, 7.8 and 10.8" H_2O static pressure. This allows us to plot the relationship between static pressure and air flow rate, and to use this relationship to determine air flow rate for any static pressure on Boiler I.

The test data are presented in Figure 5-2 and Table 5-4. From these data it is calculated that 10.8" H_2O of overfire air accounts for 14% of the combustion air at 100% load and 8% O_2. Under "normal" operating conditions of

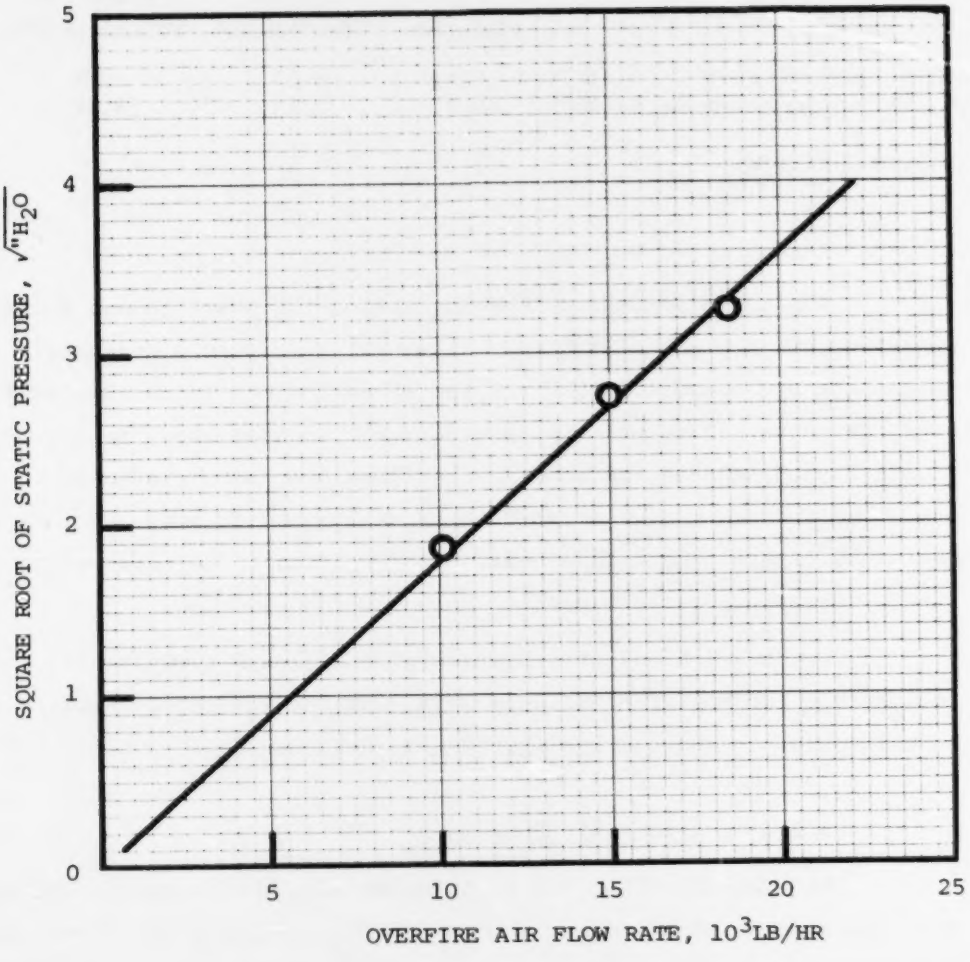

Figure 5-2. Relationship Between Overfire Air Flow Rate and Static Pressure Within the Overfire Air Duct - Test Site I.

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of 3.5" H_2O overfire air pressure, the overfire air accounts for only 8% of the combustion air. This also assumes 100% load and 8% O_2.

In relating overfire air pressure to flow rate, use is made of Bernoulli's equation for fluid flow through an orifice which predicts that flow rate will be proportional to the square root of the pressure drop. For this reason, the Y-axis of Figure 5-2 is the square root of static pressure and the relationship is drawn as a straight line which crosses the XY-intercept.

TABLE 5-4

OVERFIRE AIR FLOW RATES

	Low OFA	Med OFA	High OFA
Overfire Air Static Pressure, "H_2O	3.5	7.8	10.8
Measured OFA Flow Rate, SCF/sec	37.5	56.1	68.6
Measured OFA Flow Rate, lb/hr	10.1	15.1	18.5
Percent Combustion Air Supplied by OFA*	8%	11%	14%

*Calculated combustion air requirement at full load and 8% O_2 = 134×10^3 lb/hr

5.2 EXCESS OXYGEN AND GRATE HEAT RELEASE

Tests were conducted on Boiler I at loads of 50%, 75% and 100% of the unit's design capacity. At the higher loads, excess air was varied over a wide range. This section profiles emissions and boiler efficiency as a function of these two variables.

The units chosen to present this data are percent oxygen, and grate heat release in Btu/hr-ft^2. Grate heat release, which is proportional to the unit's steam loading, was chosen because it provides a common basis for comparing this unit's emissions with those of other units tested in this program.

5.2.1 Excess Oxygen Operating Levels

The excess oxygen operating levels encountered during testing are shown in Figure 5-3. The normal or "as-found" excess oxygen ranged from a nominal 8% at full load to nearly 12% at 50% of capacity. This is comparable to other overfed stokers tested.

All but one of the particulate tests were conducted under normal excess oxygen conditions. The exception was Test 4, a low O_2, high overfire air test. Particulate tests are indicated by solid symbols in Figure 5-3. Gaseous tests for O_2, CO_2 and NO were conducted at all points shown. These included full load tests ranging all the way from 5.0 to 10.1% O_2, and 75% load tests ranging from 6.8 to 9.9% O_2.

5.2.2 Particulate Loading vs Oxygen and Grate Heat Release

Figure 5-4 profiles the uncontrolled particulate loading as a function of grate heat release. The two coals are differentiated by symbol, and the shaded area encompasses the low overfire air tests to illustrate the reduction of particulate loading due to high overfire air. This reduction was discussed previously in Section 5.1.1.

Uncontrolled particulate loading was observed to increase with grate heat release, tripling in magnitude between 50% of capacity and full load. At full load, uncontrolled particulate loading ranged from 0.90 lb/10^6 Btu at high OFA to 1.76 lb/10^6 Btu at low OFA, and averaged 1.27 lb/10^6 Btu.

The average ash carryover was 11% for all tests, but was found to vary directly with load and inversely with overfire air. Table 5-5 presents the ash carryover data for the six particulate tests for which complete data were available.

It is noted that the single Kentucky coal data point indicates a higher ash carryover than all of the Ohio coal data points. This may be a trend but more data would be required to establish it as such.

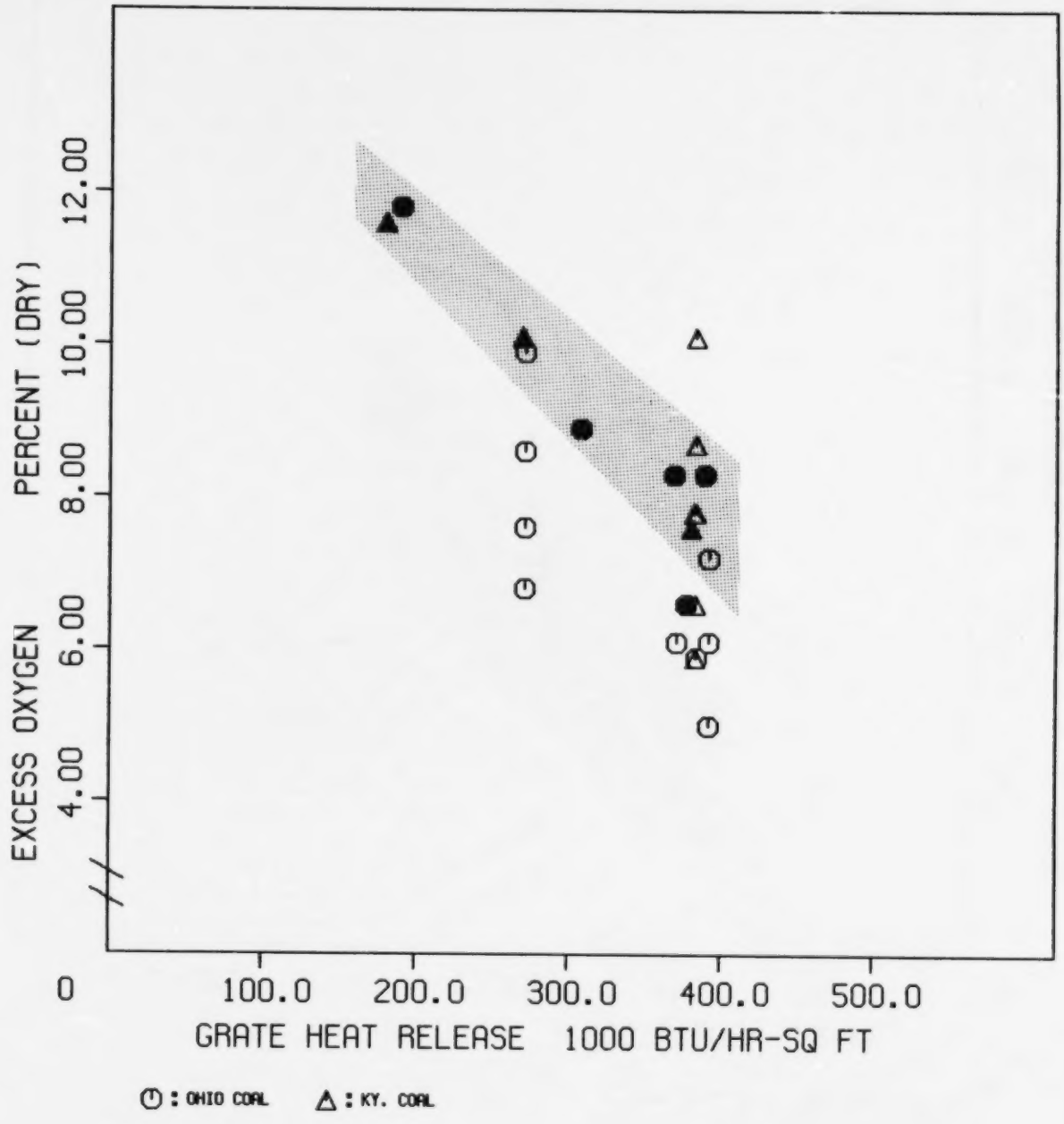

FIG. 5-3

EXCESS OXYGEN VS. GRATE HEAT RELEASE
TEST SITE I

THIS PLOT SHOWS THE RANGE IN OXYGEN LEVEL UNDER WHICH TESTS WERE CONDUCTED AT SITE I. THE SHADED AREA ENCOMPASSES THE NORMAL OR "AS-FOUND" TEST CONDITIONS, AND THE SOLID SYMBOLS REPRESENT TEST CONDITIONS FOR THE EIGHT PARTICULATE TESTS.

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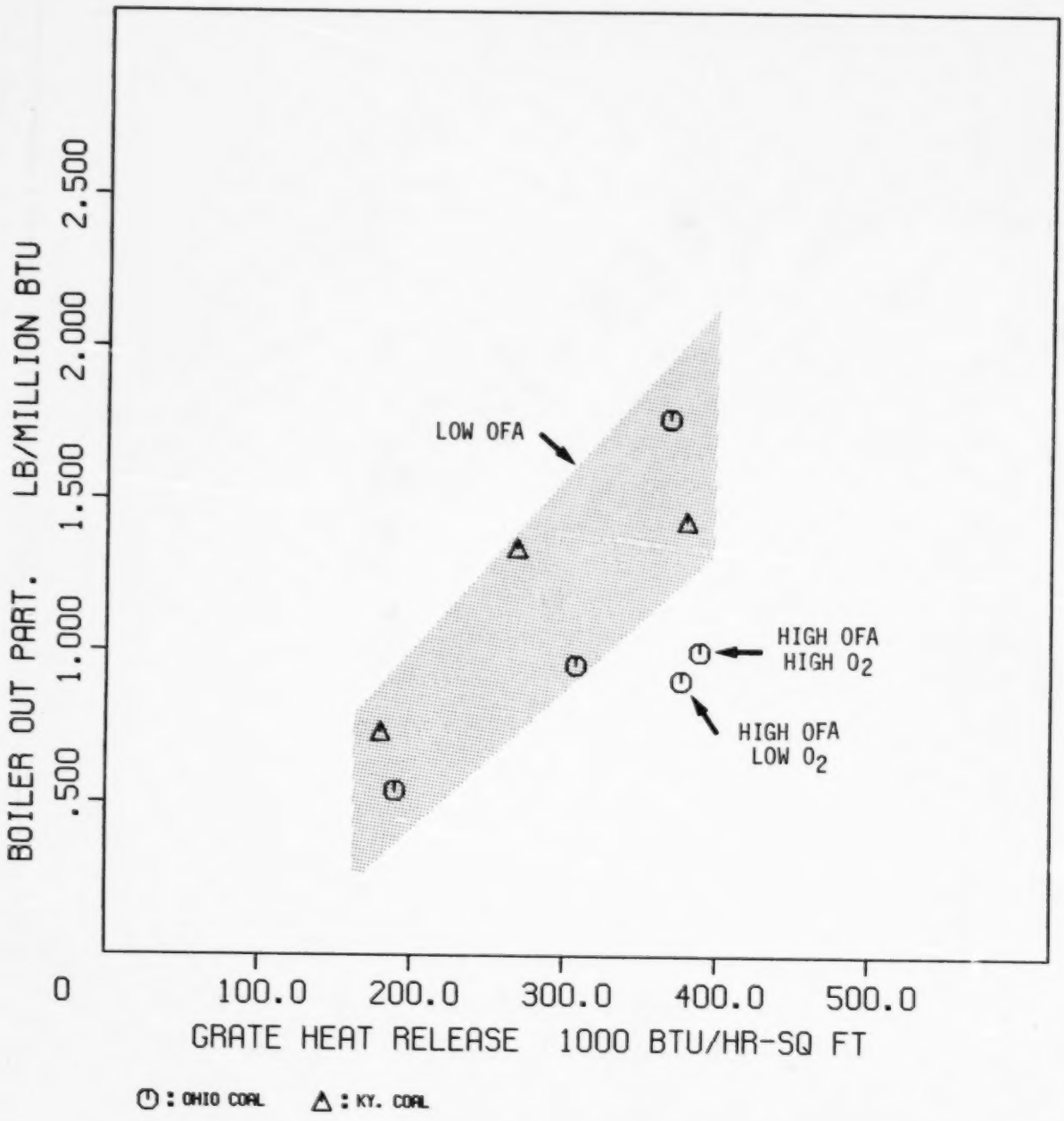

FIG. 5-4

BOILER OUT PART. VS. GRATE HEAT RELEASE
TEST SITE I

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TABLE 5-5

ASH CARRYOVER VS FIRING CONDITIONS

Test No.	Firing Condition				Ash in Coal lb/10^6Btu	Ash in Flyash lb/10^6Btu	Ash Carryover %
	Load	O_2	OFA	Coal			
2	100%	Norm	Low	Ohio	7.09	1.116	15.7
3	100%	Norm	High	Ohio	7.10	0.779	11.0
4	100%	Low	High	Ohio	8.19	0.673	8.2
5	75%	Norm	Low	Ohio	8.31	0.683	8.2
14	75%	Norm	Low	Ky	5.40	0.968	17.9
1	50%	Norm	Low	Ohio	7.99	0.417	5.2

Figure 5-5 plots the uncontrolled particulate data as a function of oxygen. Data sets are connected by lines and labeled to isolate them from the variables of load and overfire air (OFA). The data shows that particulate loading increases with increasing oxygen at 75% and 100% load.

5.2.3 Nitric Oxide vs Oxygen and Grate Heat Release

Nitric oxide (NO) concentration was measured during each test in units of parts per million (ppm) by volume. A chemiluminescent NOx analyzer was used to make these measurements. The units have been converted from ppm to lb/10^6 Btu in this report so that they can be more easily compared with existing and proposed emission standards. Table 2-2 in the Executive Summary lists the nitric oxide data in units of ppm for the convenience of those who prefer these units.

Figure 5-6 presents the nitric oxide data as a function of grate heat release under the various excess oxygen conditions encountered during testing. Two trends are evident: NO tends to decrease with increasing load and the Kentucky coal has lower NO than the Ohio coal under similar load conditions. This conclusion is further illustrated in Table 5-6.

Figures 5-7 and 5-8 present the nitric oxide data as a function of oxygen for the two coals tested. Again, there is no evidence of a separation

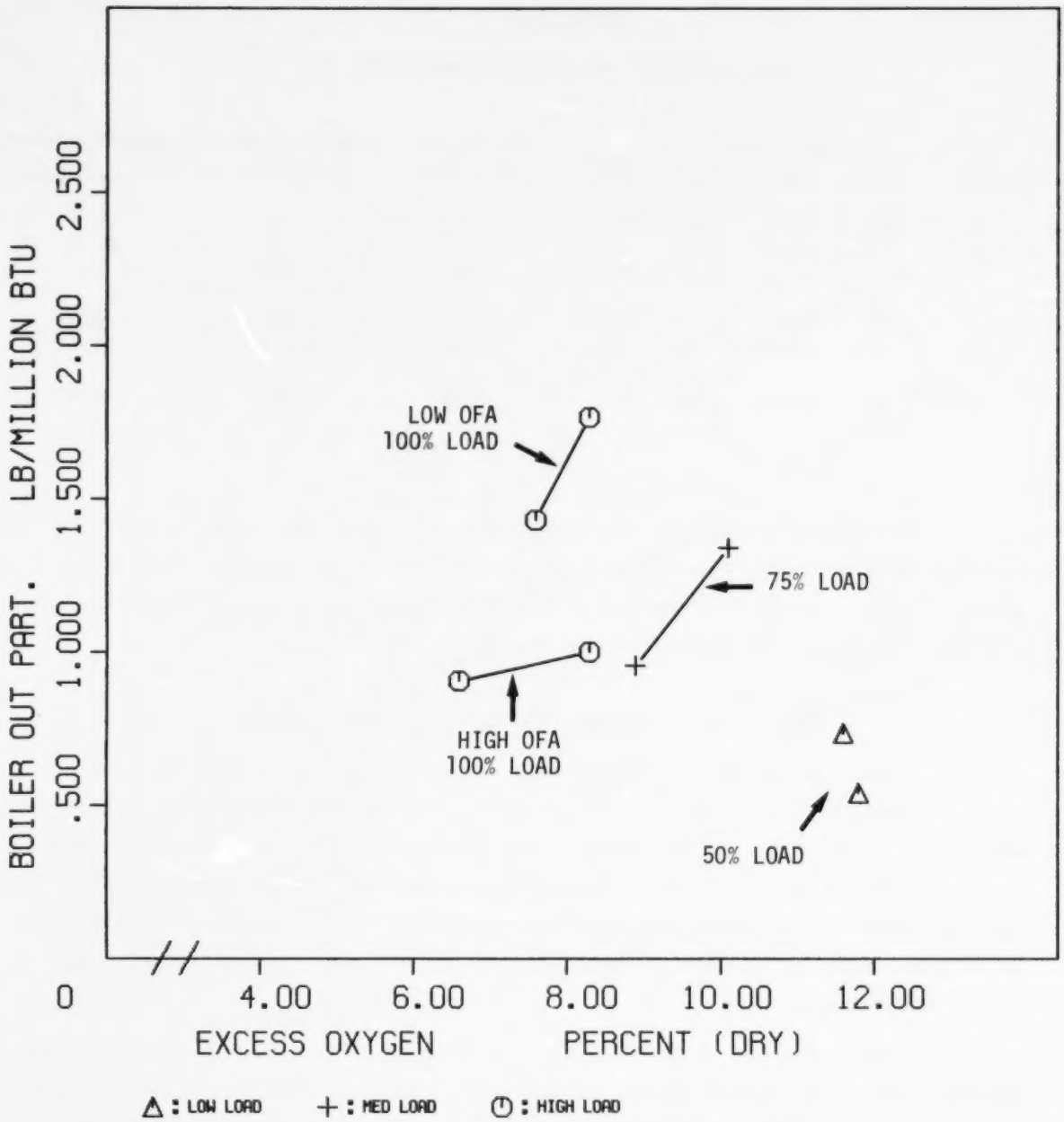

FIG. 5-5
BOILER OUT PART. VS. EXCESS OXYGEN
TEST SITE I

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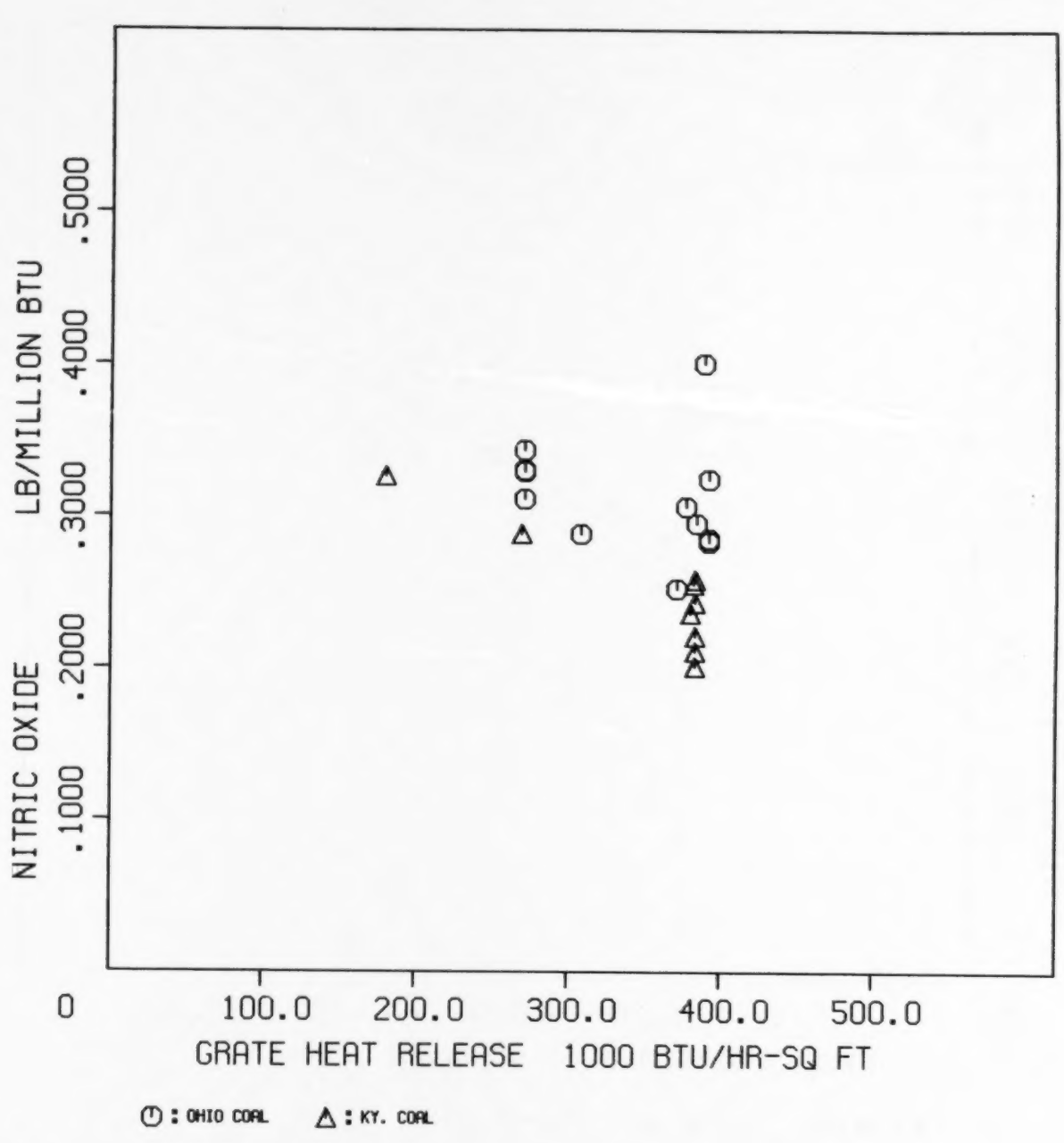

FIG. 5-6

NITRIC OXIDE VS. GRATE HEAT RELEASE
TEST SITE I

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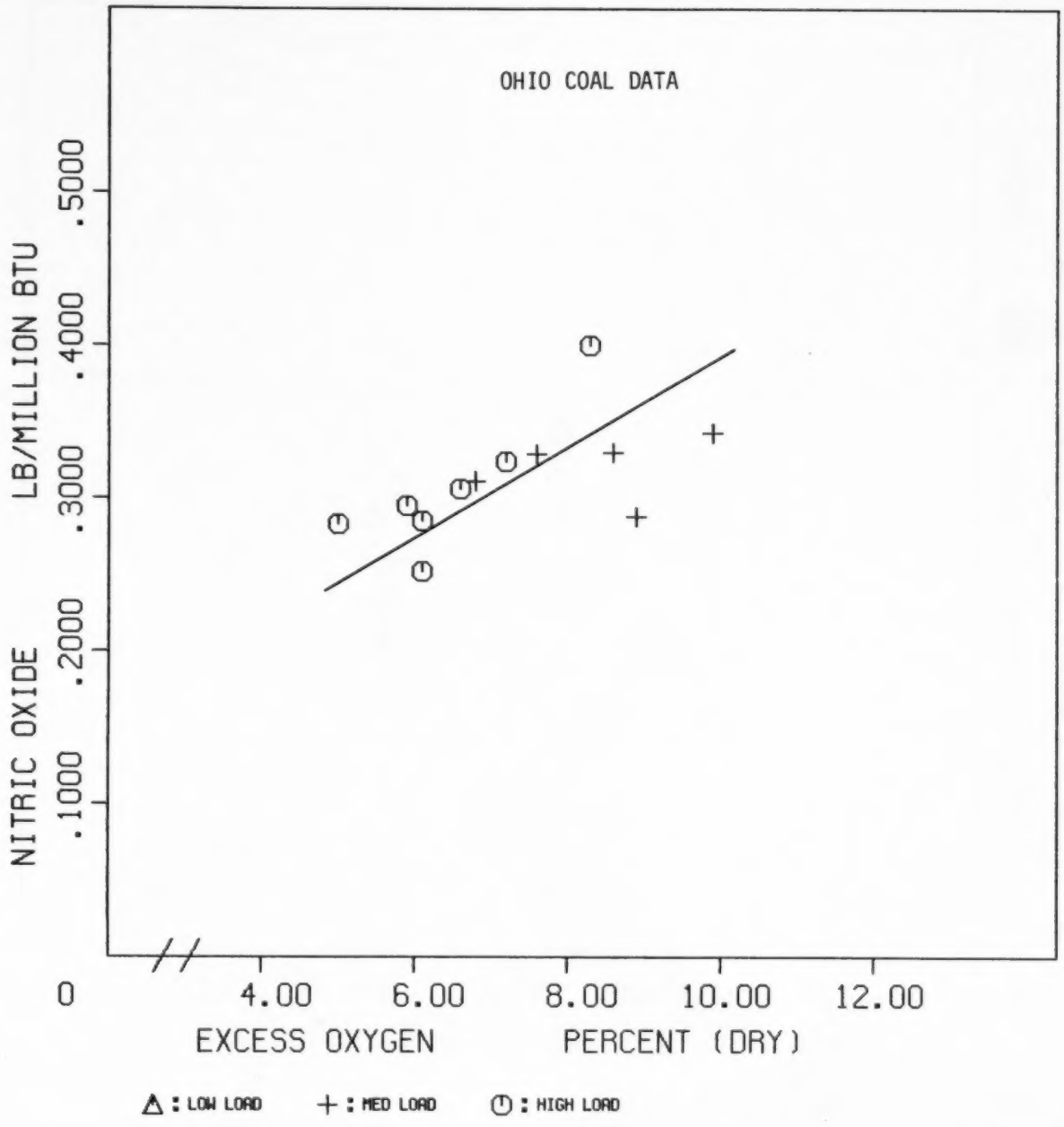

FIG. 5-7

NITRIC OXIDE VS. EXCESS OXYGEN

TEST SITE I

TREND LINE DETERMINED BY LINEAR REGRESSION ANALYSIS,
SLOPE = 0.030, COEFFICIENT OF DETERMINATION (R) = 0.60

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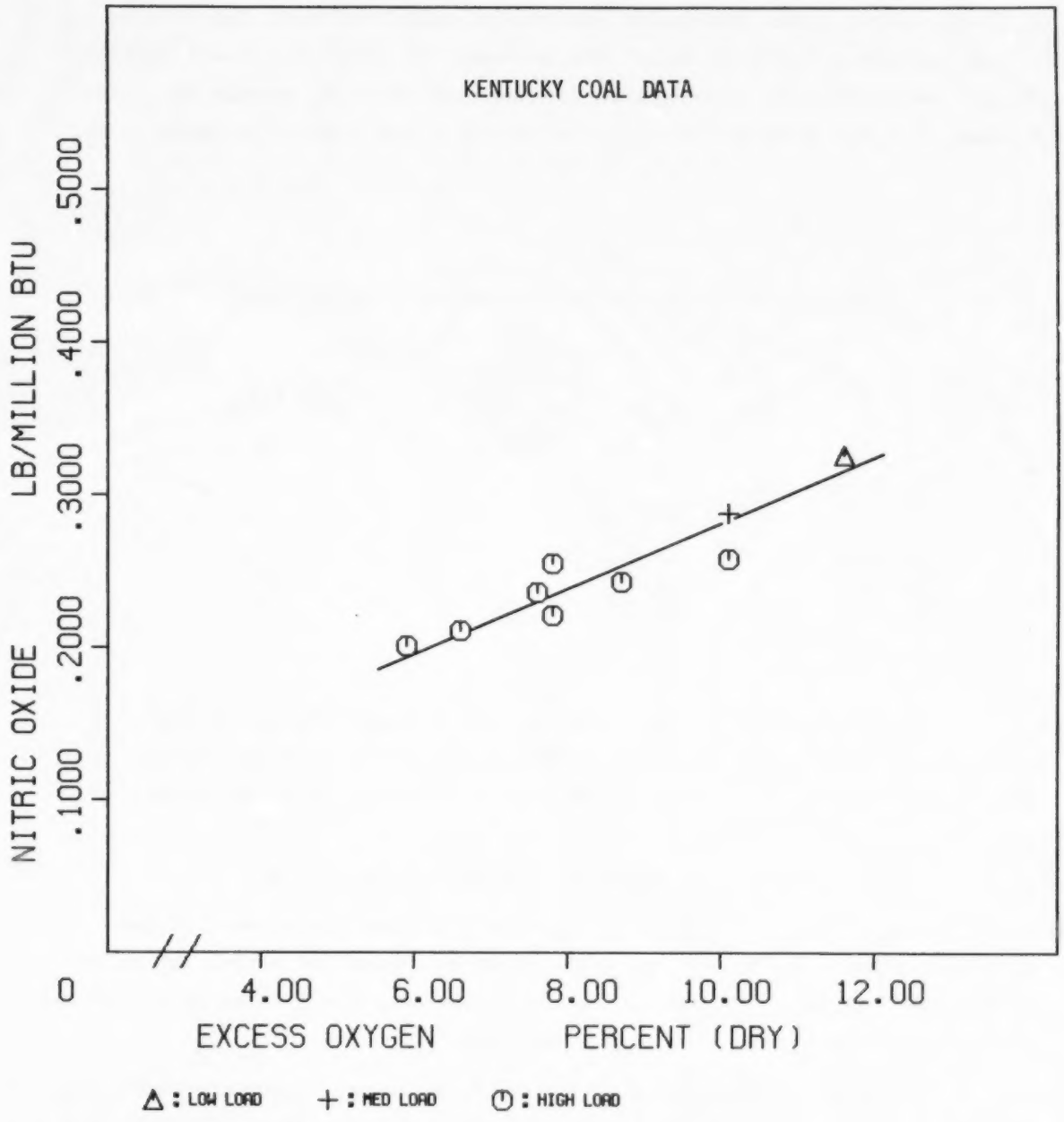

FIG. 5-8

NITRIC OXIDE VS. EXCESS OXYGEN

TEST SITE I

TREND LINE DETERMINED BY LINEAR REGRESSION ANALYSIS, SLOPE = 0.021, COEFFICIENT OF DETERMINATION (R) = 0.94. THIS PLOT SHOWS THAT BOILER LOAD, AS INDICATED BY THE THREE SYMBOLS, HAS NO APPARENT EFFECT ON EMISSION LEVEL AT CONSTANT O_2.

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by load. Using linear regression analysis on full load Tests 16a through 16e yields a slope of 0.014 lb NO/10^6 Btu increase for each one percent increase in O_2. Using the same technique on 75% capacity Tests 8a through 8d yields a slope of 0.010 lb NO/10^6 Btu increase for each one percent increase in O_2.

TABLE 5-6

AVERAGE NITRIC OXIDE CONCENTRATIONS VS LOAD AND COAL

	Coal	% O_2	Nitric Oxide lb/10^6 Btu	Nitric Oxide ppm @ 3% O_2
100% Load	Ohio	6.5	0.306	225
75% Load	Ohio	8.4	0.320	236
50% Load	Ohio	11.8	--	--
100% Load	Ky	7.8	0.232	172
75% Load	Ky	10.1	0.288	213
50% Load	Ky	11.6	0.326	245

The increase of nitric oxide as load decreases is due to the accompanying increase in oxygen. On this boiler it appears that boiler load at constant O_2 has little if any effect on nitric oxide emissions.

5.2.4 Combustibles in the Ash vs Grate Heat Release

Flyash and bottom ash samples were collected during most of the particulate tests and baked in a high temperature oven for determination of combustible content. The combustible determinations are plotted as a function of grate heat release in Figures 5-9 and 5-10.

In general, the percent of combustibles in the flyash increased with load while combustibles in the bottom ash decreased with load. Overfire air had the effect of reducing combustibles in the flyash while increasing combustibles in the bottom ash. Kentucky coal had less combustible material in its bottom ash than did Ohio coal. Flyash combustibles ranged from 22 to 37% and averaged 27%. Bottom ash combustibles ranged from 14 to 45% and averaged 29%.

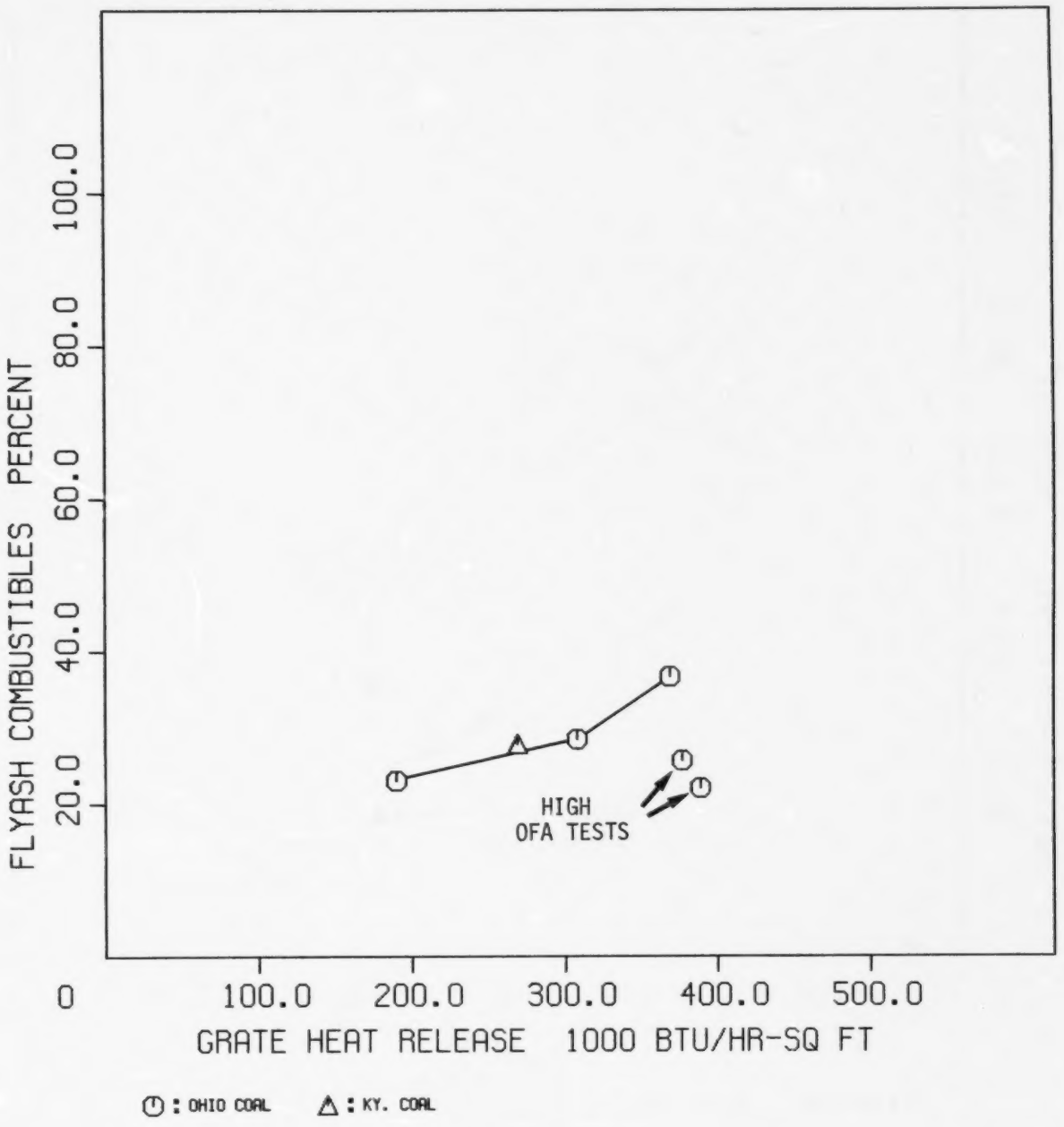

FIG. 5-9

FLYASH COMBUSTIBLES VS. GRATE HEAT RELEASE
TEST SITE I

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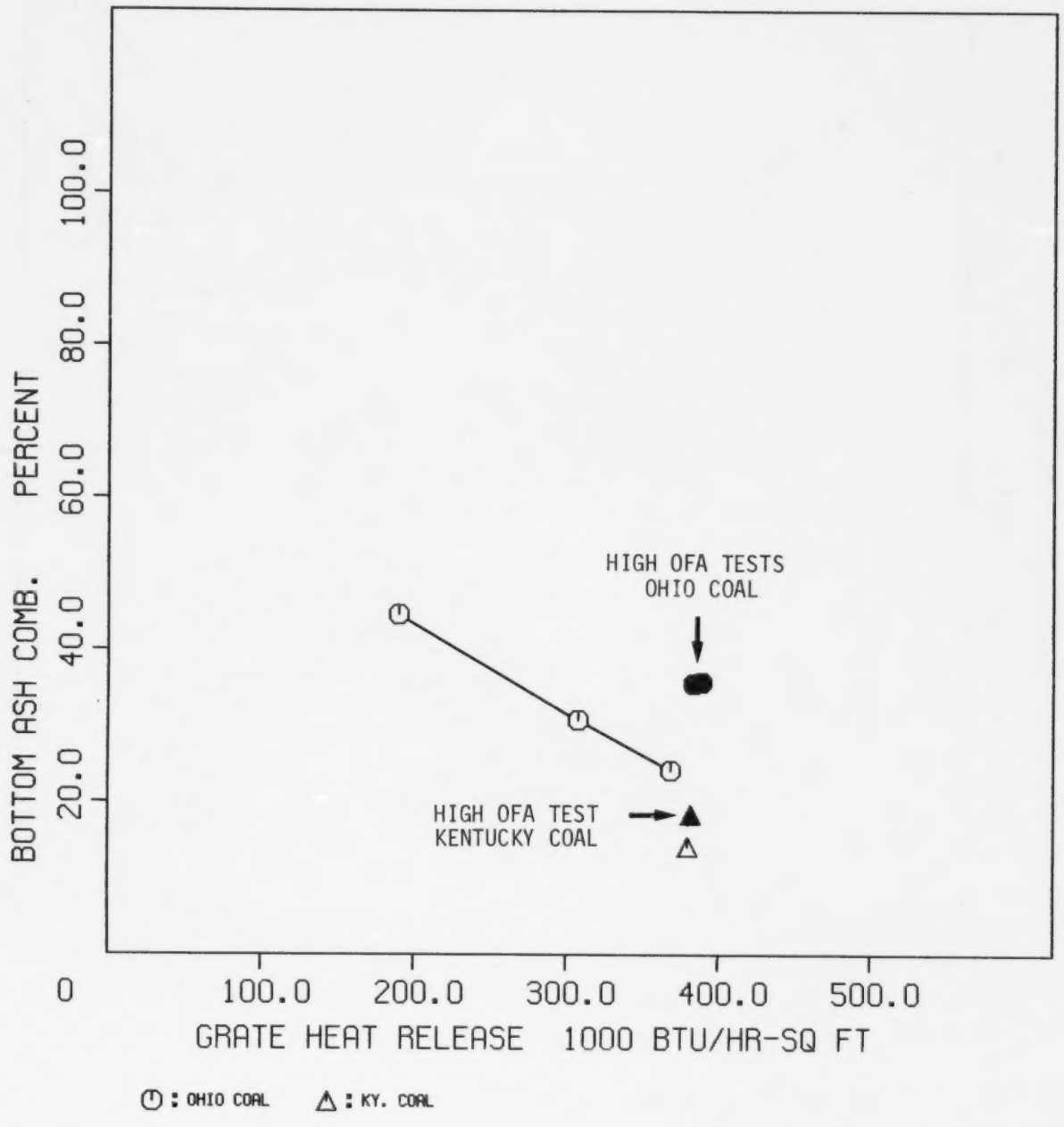

FIG. 5-10

BOTTOM ASH COMB. VS. GRATE HEAT RELEASE
TEST SITE I

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5.2.5 Boiler Efficiency vs Grate Heat Release

Boiler efficiency was determined using the ASME heat loss method for all tests which included a particulate mass loading or SASS determination. The boiler efficiencies are plotted in Figure 5-11 as a function of grate heat release. On the average, boiler efficiency was highest at full load and decreased as load decreased. Table 5-7 shows that dry gas loss was the primary factor causing boiler efficiency to drop at low loads.

TABLE 5-7

BOILER EFFICIENCY VS LOAD

	AVERAGE HEAT LOSSES, %					BOILER EFFICIENCY %
	Dry Gas	Flyash Combustibles	Bottom Ash Combustibles	Radiation	Other	
100% Load	15.19	0.50	3.47	0.54	6.28	74.02
75% Load	16.47	0.46	3.04	0.71	6.17	73.15
50% Load	18.09	0.24	4.81	1.09	6.18	69.59

5.3 COAL PROPERTIES

Two coals were tested in Boiler I. These coals are identified in this report as Ohio and Kentucky (abbreviated Ky) coals. This section discusses the chemical and physical properties of these two coals, and discusses their observed influence on boiler emissions and efficiency.

5.3.1 Chemical Composition of the Coals

Representative coal samples were obtained during each particulate and SASS test. From each sample, a proximate analysis was obtained. In addition, an ultimate analysis was obtained on three of the samples and mineral analysis of the ash was obtained on one sample.

Composite coal samples, containing portions of each individual sample, were also collected for each coal. The composite samples were given complete coal analysis including proximate, ultimate, ash fusion and minerals in the ash.

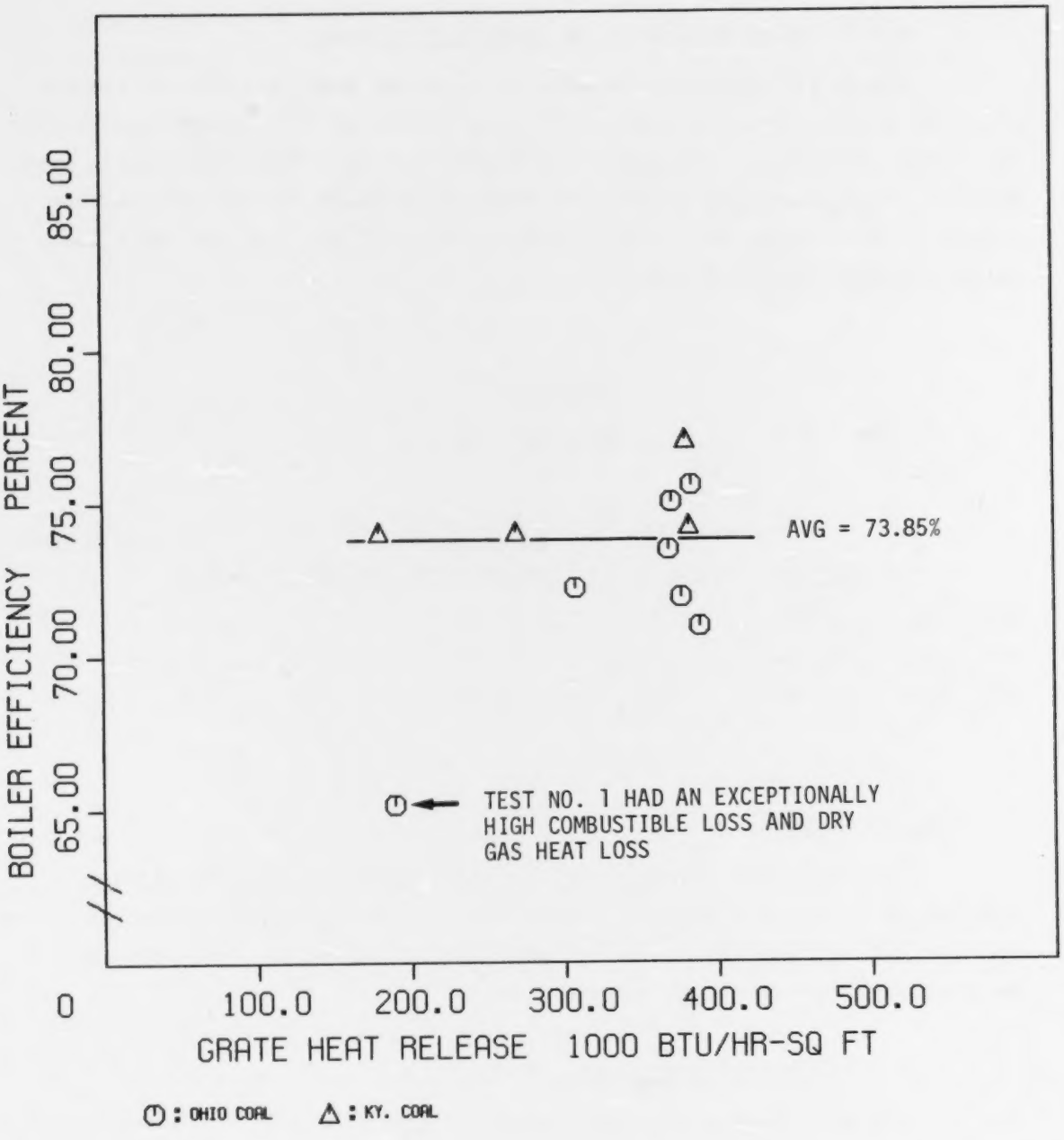

FIG. 5-11
BOILER EFFICIENCY VS. GRATE HEAT RELEASE
TEST SITE I

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The moisture, ash and sulfur content of the two coals are compared on a heating value basis in Table 5-8. Such a comparison is often more meaningful than percentage by weight. This table shows the Kentucky coal to be the better coal in terms of its lower moisture, ash and sulfur, and its higher heating value.

TABLE 5-8

COAL PROPERTIES CORRECTED TO A CONSTANT 10^6 BTU BASIS

	Ohio Coal	Kentucky Coal
Moisture, lb/10^6Btu	2.6	1.6
Ash, lb/10^6Btu	7.4	7.1
Sulfur, lb/10^6Btu	2.2	1.1
Heating Value, Btu/lb	12,858	13,823

The coal analysis for each individual sample are tabulated in Tables 5-9, 5-10 and 5-11.

5.3.2 Coal Size Consistency

Coal size consistency was determined for each coal sample obtained at Site I. The individual coal samples were screened at the site using 1", 1/2", 1/4", #8 and #16 square mesh screens. The results of these screenings are presented in Table 5-12. It is noted that the Kentucky coal, which was considered the better coal in terms of moisture, ash, sulfur and heating value, averaged slightly lower fines than the Ohio coal.

The coal size consistency measurements are presented on a statistical basis in Figures 5-12 and 5-13. Here, the standard deviation of the coal size consistency measurements are compared with the ABMA recommended limits for overfed stokers. Both coals are sized on the low fines side of the ABMA recommended limits for overfeed stokers. This sizing is considered acceptable and should have no undesirable effects on the emissions.

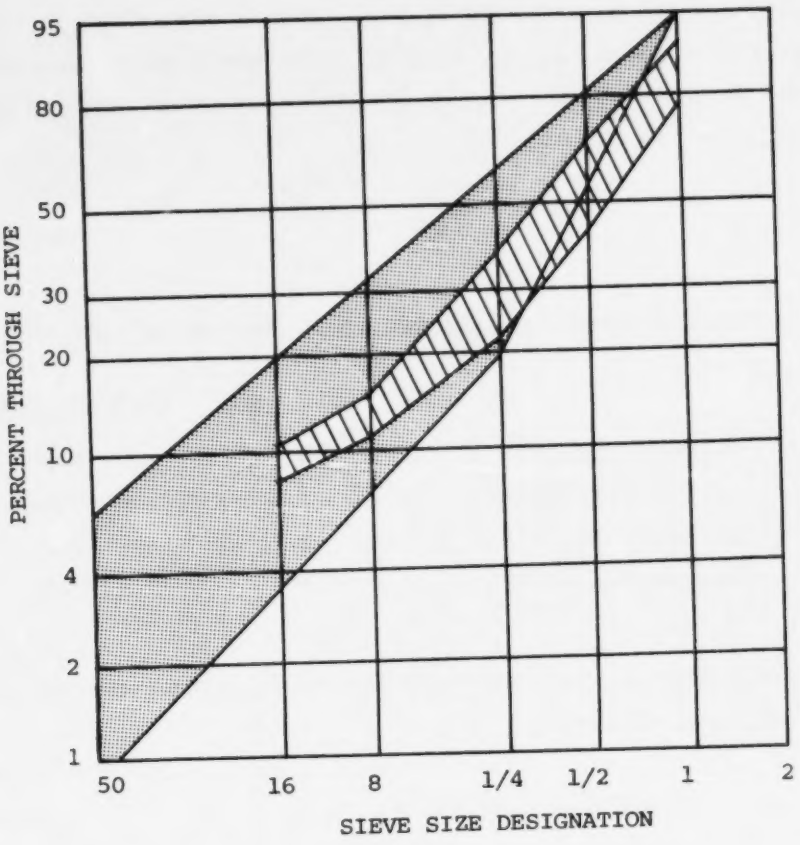

Figure 5-12. Size Consistency of "As-Fired" Ohio Coal vs ABMA Recommended Limits of Coal Sizing for Overfeed Stokers - Test Site I.

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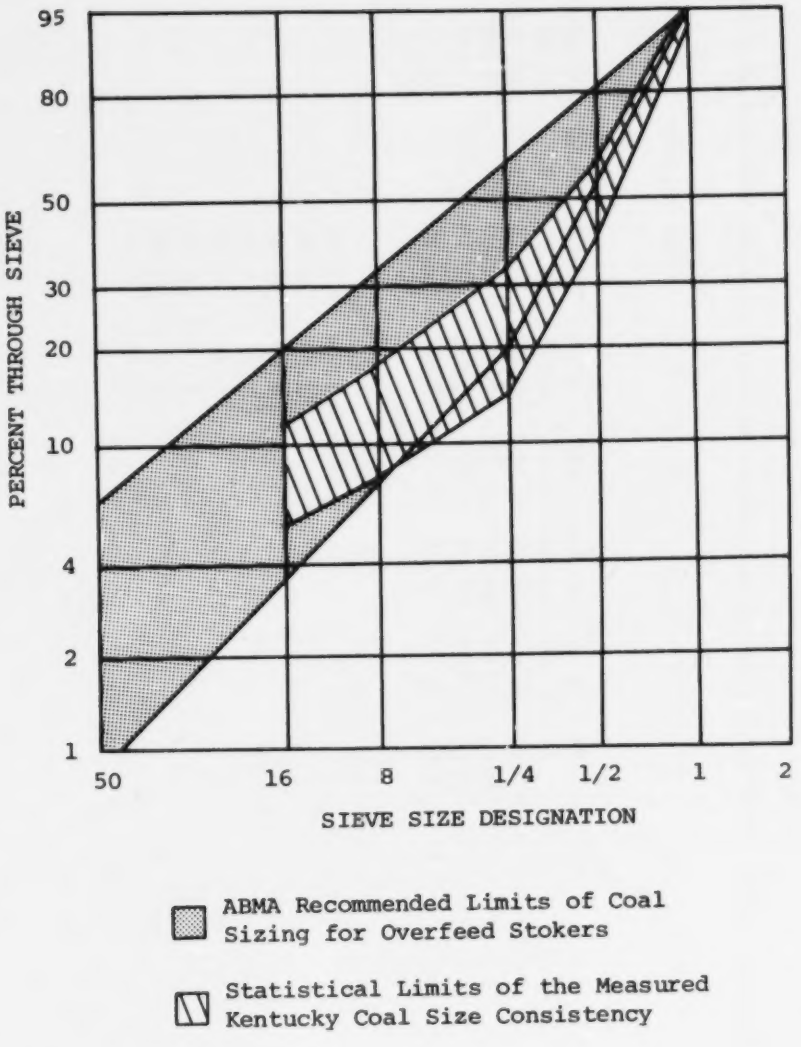

Figure 5-13. Size Consistency of "As-Fired" Kentucky Coal vs ABMA Recommended Limits of Coal Sizing For Overfeed Stokers - Test Site I.

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TABLE 5-9

FUEL ANALYSIS - OHIO COAL
TEST SITE I

TEST NO.	1	2	3	4	5	6	9	COMP	AVG	STD DEV
PROXIMATE (As Rec)										
% Moisture	4.08	3.76	3.28	3.50	2.69	2.67	2.96	3.08	3.28	0.54
% Ash	10.09	9.05	9.15	10.37	10.58	9.38	8.37	10.07	9.57	0.80
% Volatile	37.43	38.10	37.96	38.61	38.05	37.84	38.15	38.16	38.02	0.36
% Fixed Carbon	48.40	49.09	49.61	47.52	48.68	50.11	50.52	48.69	49.05	1.02
Btu/lb	12634	12757	12881	12660	12739	13024	13308	12718	12858	240
% Sulfur	3.50	3.14	2.81	2.83	2.98	2.28	1.88	2.95	2.77	0.54
ULTIMATE (As Rec)										
% Moisture							2.96	3.08		
% Carbon							72.62	70.30		
% Hydrogen							4.97	4.88		
% Nitrogen							1.26	1.76		
% Chlorine							0.40	0.16		
% Sulfur							1.88	2.95		
% Ash							8.37	10.07		
% Oxygen (diff)							7.54	6.80		
ASH FUSION (Red)										
Initial Deformation								2060°F		--
Softening (H=W)								2195°F		--
Softening (H=1/2W)								2335°F		--
Fluid								2465°F		--
EQUILIBRIUM MOISTURE								4.43	4.43	--
HARDGROVE GRINDABILITY								50	50	--
FREE SWELLING INDEX										

TABLE 5-10

FUEL ANALYSIS - KENTUCKY COAL
TEST SITE I

TEST NO.	10	14	15	18	COMP	AVG	STD DEV
PROXIMATE (As Rec)							
% Moisture	2.47	2.10	2.50	1.97	2.32	2.26	0.27
% Ash	5.23	7.32	6.14	5.45	6.46	6.04	0.94
% Volatile	39.38	37.87	38.38	39.53	37.79	38.79	0.80
% Fixed Carbon	52.92	52.71	52.98	53.05	53.43	52.92	0.15
Btu/lb	14053	13558	13687	13995	13708	13823	239
% Sulfur	1.43	1.75	1.46	1.33	1.43	1.49	0.18
ULTIMATE (As Rec)							
% Moisture	2.42			1.97	2.32	2.20	0.32
% Carbon	76.57			77.88	76.05	77.23	0.93
% Hydrogen	5.34			5.22	5.15	5.28	0.08
% Nitrogen	1.51			1.49	1.40	1.50	0.01
% Chlorine	0.13			0.13	0.14	0.13	0.00
% Sulfur	1.43			1.33	1.43	1.38	0.07
% Ash	5.23			5.45	6.46	5.34	0.16
% Oxygen (diff)	7.32			6.53	7.05	6.93	0.56
ASH FUSION (Red)							
Initial Deformation				2065°F	2075°F		
Softening (H=W)				2235°F	2225°F		
Softening (H=1/2W)				2415°F	2365°F		
Fluid				2575°F	2535°F		
HARDGROVE GRINDABILITY					48	48	--
FREE SWELLING INDEX					4	4	--

TABLE 5-11

MINERAL ANALYSIS OF COAL ASH
(PERCENT BY WEIGHT)
TEST SITE I

Coal Test No.	Ohio Composite	Kentucky 18	Kentucky Composite
Silica, SiO_2	38.94	42.57	43.98
Alumina, Al_2O_3	23.04	25.24	23.64
Titania, TiO_2	1.22	1.59	1.42
Ferric Oxide, Fe_2O_3	27.22	18.87	17.78
Lime, CaO	2.39	2.99	3.44
Magnesia, MgO	0.81	0.75	0.79
Potassium Oxide, K_2O	1.93	1.48	1.75
Sodium Oxide, Na_2O	0.33	0.96	0.73
Sulfur Trioxide, SO_3	1.55	3.08	3.64
Phos. Pentoxide, P_2O_5	0.34	0.26	0.28
Strontium Oxide, SrO	0.00	0.18	0.05
Barium Oxide, BaO	0.04	0.36	0.25
Manganese Oxide, Mn_3O_4	0.05	0.02	0.02
Undetermined	2.14	1.65	2.23
	100.00	100.00	100.00
Alkalies as Na_2O, dry	--	0.11	--
Silica Value	56.14	65.31	66.65
Base: Acid Ratio	0.52	0.36	0.35
T_{250} Temperature, °F	2295	2460	2470
% Equilibrium Moisture	4.43	--	--
Hardgrove Grindability Index	50	--	48
Free Swelling Index	--	--	4
Fouling Index	0.17	0.35	--
Slagging Index	1.52	0.49	--
% Pyritic Sulfur	1.70	0.55	0.65
% Sulfate Sulfur	0.06	0.02	0.03
% Organic Sulfur	1.19	0.76	0.75

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TABLE 5-12

AS-FIRED COAL SIZE CONSISTENCY
TEST SITE I

	Test No.	PERCENT PASSING STATED SCREEN SIZE 1"	1/2"	1/4"	#8	#16
OHIO COAL	01	95.6	79.6	45.4	17.2	10.4
	02	87.9	63.2	37.2	16.2	10.2
	03	82.2	49.7	21.8	11.1	8.2
	04	79.0	44.5	23.7	12.9	8.2
	05	78.1	48.5	27.3	14.3	10.0
	06	83.2	47.7	25.0	12.4	8.7
	09	85.6	54.9	30.8	14.9	10.1
	Comp	85.2	59.4	33.4	15.5	10.3
	Average	84.5	55.4	30.2	14.1	9.4
KENTUCKY COAL	10	93.8	51.3	24.5	13.1	8.1
	14	96.6	57.8	31.6	17.8	12.1
	15	93.9	57.8	30.3	16.0	9.8
	18	94.6	36.4	10.8	5.9	4.7
	Comp	96.5	52.8	24.5	13.6	8.8
	Average	94.7	50.8	24.3	13.2	8.7

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5.3.3 Effect of Coal Properties on Emissions and Efficiency

The observed influence which changing coal properties had on boiler emissions and efficiency is discussed below. Frequent references are made to figures in Section 5.2, Excess Oxygen and Grate Heat Release, which illustrate the differences in emissions between the two coals.

Excess Oxygen Operating Conditions. In general, both coals were tested under similar excess oxygen conditions. There are no data indicating that one coal required more excess oxygen than the other. Figure 5-3 shows the oxygen levels under which the various tests were run for each coal.

Particulate Mass Loading. The two coals produced similar particulate mass loadings even though the Kentucky coal was lower in ash. Table 5-13 presents three sets of data where coal is the variable. In each case the Kentucky coal had less ash than the Ohio coal, but in two out of three cases, the Ohio coal had a lower particulate mass loading. The differences are viewed as normal data scatter and, as such, are not given any significance. There are not enough data here to say with any certainty that one coal produces higher particulate loadings than the other. For a graphical presentation of this data refer back to Figure 5-4 in Section 5.2.

TABLE 5-13

PARTICULATE LOADING VS COAL ASH

	Boiler Capacity, %	Ash in Coal lb/10^6Btu	Particulate Mass Loading lb/10^6Btu	Particulate Mass Loading % of Ash in Coal
Ohio Coal	100	7.09	1.76	25
Kentucky Coal	100	4.49	1.43	32
Ohio Coal	75	8.31	0.95	11
Kentucky Coal	75	5.40	1.34	25
Ohio Coal	50	7.99	0.54	7
Kentucky Coal	50	3.72	0.73	20

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Nitric Oxide. Nitric oxide concentrations were as much as 36% lower for Kentucky coal than for Ohio coal under similar firing conditions. The reason for this behavior has not been ascertained, but the evidence for it is strong. Table 5-14 presents three sets of data where coal is the variable. It is seen that the difference is greatest at full load and high O_2.

TABLE 5-14

NITRIC OXIDE VS COAL

	Test No.	Firing Conditions			Nitric Oxide lb/10^6Btu	Difference %
		% Load	% O_2	OFA		
Ohio Coal	3	103	8.3	High	0.400	--
Kentucky Coal	18	101	7.8	High	0.255	-36%
Ohio Coal	7b	104	6.1	Low	0.285	--
Kentucky Coal	16c	102	5.9	Low	0.201	-29%
Ohio Coal	8a	72	9.9	Low	0.343	--
Kentucky Coal	14	71	10.1	Low	0.288	-16%

The evidence for Kentucky coal's lower nitric oxide concentrations are illustrated graphically in Figure 5-1 of Section 5.1, and also in Figures 5-7, and 5-8 of Section 5.2.

It should be noted that Kentucky coal contained 26% less nitrogen on a heating value basis than did Ohio coal. However, fuel nitrogen and nitric oxide emissions have not correlated well at previous test sites. Thus, no conclusions about their relationship will be made until all the data are examined in the Final Project report.

Sulfur Dioxide. Sulfur dioxide (SO_2) and sulfur trioxide (SO_3) were measured during one test on each of the two coals. Each test consisted of two repetitions of the Shell Emeryville method and one repetition of EPA Method 6. The test data are presented in Table 5-15 and compared with the sulfur content of the coal sample obtained during each test.

TABLE 5-15

SULFUR OXIDES VS FUEL SULFUR

	Method	lb SOx/10^6Btu SO_2	lb SOx/10^6Btu SO_3	Fuel Sulfur lb/10^6Btu as SO_2	Conversion Factor, %
Ohio Coal (Test 9)	Shell	4.151	0.053	2.825	149
	Meth 6	3.105	0.058	2.825	112
	Shell	3.554	0.048	2.825	128
Kentucky Coal (Test 18)	Shell	1.781	0.020	1.901	95
	Meth 6	2.104	0.008	1.901	111
	Shell	1.675	0.008	1.901	89

The conversion factor in Table 5-15 is the percentage of fuel sulfur which is converted to SO_2 and SO_3. For Test 9, because the conversion factors for all three SOx repetitions are greater than 100, it is believed that the fuel sulfur determination was low. The average conversion factor for Test 18 is 98%, which is the expected value. The remaining two percent of the fuel sulfur is assumed to be retained in the ash.

Combustibles in the Ash. Combustibles in the flyash were invarient with coal, averaging 27.1% for five Ohio coal tests and 27.8% for the single determination on Kentucky coal. These data were presented graphically in Figure 5-9.

Combustibles in the bottom ash were less while firing Kentucky coal than while firing Ohio coal. Overall, bottom ash combustibles averaged 34.2% in the Ohio coal and 16.3% in the Kentucky coal. These data were presented in Figure 5-10.

Boiler Efficiency. Kentucky coal resulted in a 3% higher boiler efficiency than Ohio coal. As seen in Table 5-16, combustible heat losses account for this difference. More specifically, it was the heat loss due to combustibles in the bottom ash which accounted for the difference.

TABLE 5-16

BOILER EFFICIENCY VS COAL

		BOILER HEAT LOSSES, %				BOILER EFFICIENCY %
		Dry Gas	Moisture Related	Combus-tible	Other	
Ohio Coal	(Test 2)	15.9	5.0	3.6	2.0	73.5
Kentucky Coal	(Test 15)	14.8	4.7	1.4	2.0	77.1
Ohio Coal	(Test 3)	16.7	4.9	5.4	2.0	71.0
Kentucky Coal	(Test 18)	17.5	4.7	1.5	2.0	74.3
Ohio Coal	(Test 5)	15.6	4.8	5.2	2.2	72.2
Kentucky Coal	(Test 14)	17.3	4.6	1.8	2.2	74.1

5.4 SOURCE ASSESSMENT SAMPLING SYSTEM (SASS)

Two SASS tests were run at Test Site I. These two tests, nos. 9 and 18, were conducted at full load and high overfire air on each of the two coals. The SASS samples have been processed by combined gas chromatography/mass spectroscopy for total polynuclear content, seven specific polynuclear aromatic hydrocarbons (Table 5-17), and trace elements.

Particle size distribution of the flyash as determined by the three cyclones in the SASS train are presented in Figure 5-14. All other SASS test results will be reported under separate cover -- at the conclusion of this test program.

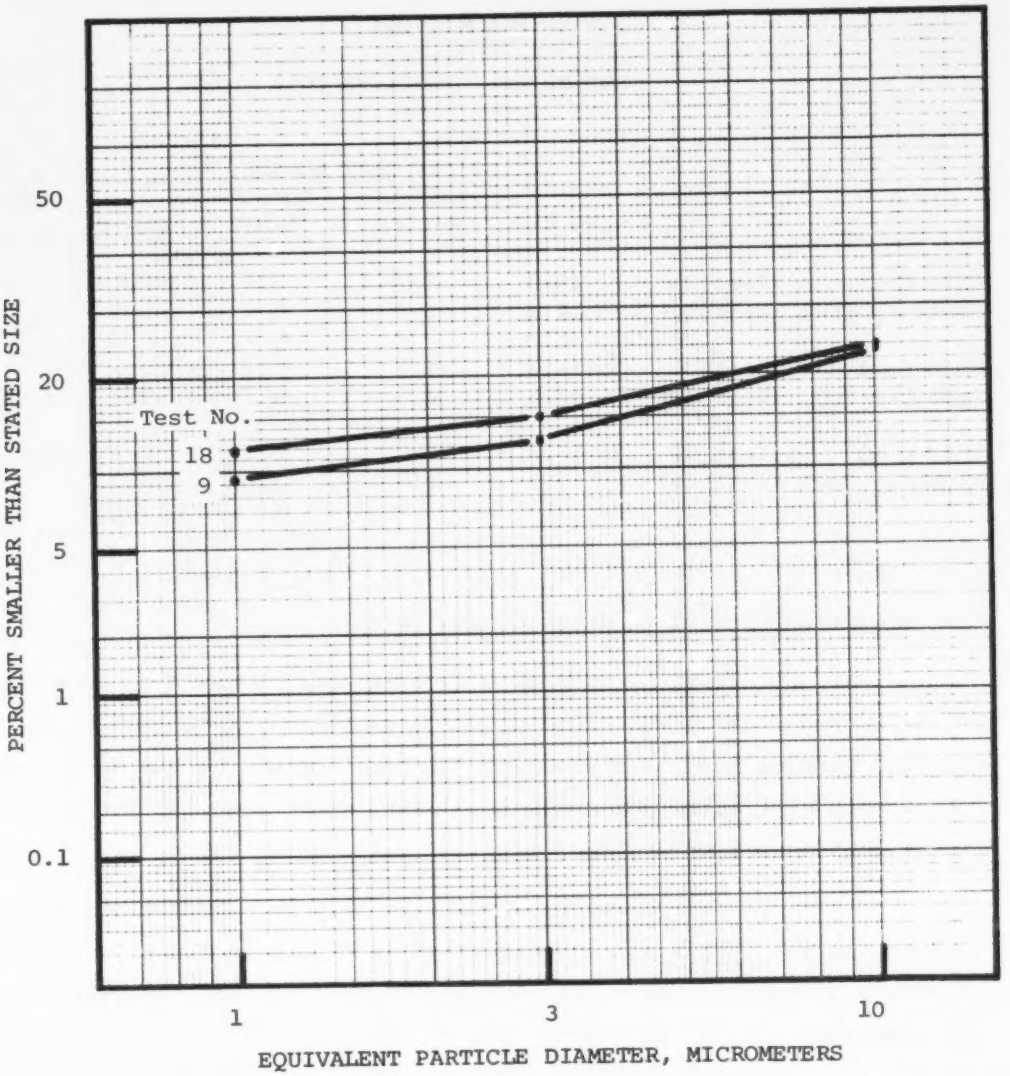

Figure 5-14. Particle Size Distribution of the Uncontrolled Particulate Matter as Determined by SASS Gravimetrics - Test Site I.

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TABLE 5-17

POLYNUCLEAR AROMATIC HYDROCARBONS
ANALYZED IN THE SITE I SASS SAMPLE

Element Name	Molecular Weight	Molecular Formula
7,12 Dimethylbenz (a) anthracene	256	$C_{20}H_{16}$
Dibenz (a,h) anthracene	278	$C_{22}H_{14}$
Benzo (c) phenanthrene	228	$C_{18}H_{12}$
3-methyl cholanthrene	268	$C_{21}H_{16}$
Benzo (a) pyrene	252	$C_{20}H_{12}$
Dibenzo (a,h) pyrene	302	$C_{24}H_{14}$
Dibenzo (a,i) pyrene	302	$C_{24}H_{14}$
Dibenzo (c,g) carbazole	267	$C_{20}H_{13}N$

5.5 DATA TABLES

Tables 5-18 through 5-21 summarize the test data obtained at Test Site I. These tables, in conjunction with Table 2-2 in the Executive Summary, are included for reference purposes.

TABLE 5-18

PARTICULATE EMISSIONS
TEST SITE I

	Test No.	Coal Type	Load %	O_2 %	EMISSIONS lb/10^6Btu	EMISSIONS gr/SCF	EMISSIONS lb/hr	Velocity ft/sec
BOILER OUTLET	01	Ohio	50.3	11.8	0.541	0.168	31	34.01
	02	Ohio	97.8	8.3	1.763	0.766	180	43.99
	03	Ohio	103.1	8.3	0.999	0.439	106	47.22
	04	Ohio	100.0	6.6	0.904	0.443	85	41.37
	05	Ohio	81.6	8.9	0.954	0.395	66	35.38
	10	Kent	50.3	11.6	0.734	0.237	31	28.09
	14	Kent	71.4	10.1	1.341	0.496	79	40.15
	15	Kent	100.0	7.6	1.430	0.658	130	39.89

TABLE 5-19

PERCENT COMBUSTIBLES IN REFUSE
TEST SITE I

	Test No.	Boiler Outlet	Bottom Ash
OHIO COAL	01	23.0	44.69
	02	36.7	24.27
	03	22.0	35.89
	04	25.6	--
	05	28.4	30.82
	09	--	35.51
	AVG	27.1	34.24
KENTUCKY COAL	14	27.8	--
	15	--	14.14
	18	--	18.39
	AVG	27.8	16.27

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TABLE 5-20

HEAT LOSSES AND EFFICIENCIES
TEST SITE I

TEST NO.	DRY GAS LOSS	MOISTURE IN FUEL	H_2O FROM COMBUSTION OF H_2	COMBUSTIBLES IN FLYASH	COMBUSTIBLES IN BOTTOM ASH	TOTAL COMBUSTIBLES IN REFUSE	RADIATION FROM BOILER	UNMEASURED	TOTAL LOSSES	BOILER EFFICIENCY
01	18.51	0.41	4.48	0.18	8.72	8.90	1.06	1.50	34.86	65.14
02	15.90	0.39	4.57	0.92	2.72	3.64	0.55	1.50	26.55	73.45
03	16.73	0.34	4.59	0.31	5.05	5.36	0.52	1.50	29.04	70.96
04	15.20	0.36	4.61	0.33	5.57	5.90	0.54	1.50	28.11	71.89
05	15.64	0.27	4.49	0.38	4.84	5.22	0.66	1.50	27.78	72.22
06	13.11	0.26	4.37	0.39	4.80	5.19	0.55	1.50	24.98	75.02
09	13.03	0.29	4.34	0.35	4.43	4.78	0.53	1.50	24.47	75.53
10	17.67	0.22	4.28	0.29	0.89	1.18	1.11	1.50	25.96	74.04
14	17.29	0.20	4.43	0.53	1.23	1.76	0.75	1.50	25.93	74.07
15	14.84	0.24	4.45	0.57	0.81	1.38	0.54	1.50	22.95	77.05
18	17.49	0.19	4.51	0.61	0.92	1.53	0.53	1.50	25.75	74.25

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TABLE 5-21

STEAM FLOWS AND HEAT RELEASE RATES
TEST SITE I

Test No.	Capacity %	Steam Flow lb/hr	Heat Input 10^6Btu/hr	Heat Output 10^6Btu/hr	Front Foot Heat Release 10^6Btu/hr-ft	Grate Heat Release 10^6Btu/hr-ft^2	Furnace Heat Release 10^3Btu/hr-ft^3
1	50	35,207	57.7	35.4	2.59	190	12.3
2	98	68,462	102.1	68.9	5.03	369	23.9
3	103	72,188	106.3	72.7	5.31	389	25.2
4	100	70,000	93.5	70.5	5.15	377	24.4
5	82	57,143	69.5	57.5	4.20	308	19.9
6	99	68,936	85.2	69.4	5.07	371	24.0
7	104	72,727	109.0	73.2	5.35	392	25.4
8	72	50,294	83.2	50.6	3.70	271	17.5
9	102	71,345	95.1	71.8	5.25	384	24.9
10	48	33,488	42.2	33.7	2.46	180	11.7
14	71	50,000	59.2	50.3	3.68	269	17.4
15	101	70,612	90.9	71.1	5.19	380	24.6
16	102	71,087	96.6	71.5	5.23	383	24.8
18	101	71,000	85.0	71.5	5.22	382	24.8

NOTE: Steam flow based on steam flow integrator readings.
Heat input based on coal flow rate and heating value.
Heat output based on steam flow and steam enthalpy minus feedwater enthalpy.
Heat release rates based on heat output and 74% boiler efficiency
because heat input data is believed to contain inaccuracies.

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APPENDIX A

CONVERSION FACTORS

ENGLISH AND METRIC UNITS TO SI UNITS

To Convert From	To	Multiply By
in	cm	2.540
in^2	cm^2	6.452
ft	m	0.3048
ft^2	m^2	0.09290
ft^3	m^3	0.02832
lb	Kg	0.4536
lb/hr	Mg/s	0.1260
$lb/10^6$BTU	ng/J	430
g/Mcal	ng/J	239
BTU	J	1054
BTU/lb	J/kg	2324
BTU/hr	W	0.2929
J/sec	W	1.000
J/hr	W	3600
BTU/ft/hr	W/m	0.9609
BTU/ft/hr	J/hr/m	3459
$BTU/ft^2/hr$	W/m^2	3.152
$BTU/ft^2/hr$	$J/hr/m^2$	11349
$BTU/ft^3/hr$	W/m^3	10.34
$BTU/ft^3/hr$	$J/hr/m^3$	37234
psia	Pa	6895
$"H_2O$	Pa	249.1
Rankine	Celsius	C = 5/9R-273
Fahrenheit	Celsius	C = 5/9(F-32)
Celsius	Kelvin	K = C+273
Rankine	Kelvin	K = 5/9R

FOR TYPICAL COAL FUEL

ppm @ 3% O_2 (SO_2)	ng/J	($lb/10^6$Btu)	0.851 ($1.98x10^{-3}$)
ppm @ 3% O_2 (SO_3)	ng/J	($lb/10^6$Btu)	1.063 ($2.47x10^{-3}$)
ppm @ 3% O_2 (NO)*	ng/J	($lb/10^6$Btu)	0.399 ($9.28x10^{-4}$)
ppm @ 3% O_2 (NO_2)	ng/J	($lb/10^6$Btu)	0.611 ($1.42x10^{-3}$)
ppm @ 3% O_2 (CO)	ng/J	($lb/10^6$Btu)	0.372 ($8.65x10^{-4}$)
ppm @ 3% O_2 (CH_4)	ng/J	($lb/10^6$Btu)	0.213 ($4.95x10^{-4}$)
g/kg of fuel**	ng/J	($lb/10^6$Btu)	4300 (10)

*Federal environmental regulations express NOx in terms of NO_2; thus NO units should be converted using the NO_2 conversion factor.

**Based on higher heating value of 10,000 Btu/lb. For a heating value other than 10,000 Btu/lb, multiply the conversion factor by 10,000/(Btu/lb).

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APPENDIX B

CONVERSION FACTORS

SI UNITS TO ENGLISH AND METRIC UNITS

To Convert From	To	Multiply By
cm	in	0.3937
cm^2	in^2	0.1550
m	ft	3.281
m^2	ft^2	10.764
m^3	ft^3	35.315
Kg	lb	2.205
Mg/s	lb/hr	7.937
ng/J	$lb/10^6$BTU	0.00233
ng/J	g/Mcal	0.00418
J	BTU	0.000948
J/kg	BTU/lb	0.000430
J/hr/m	BTU/ft/hr	0.000289
$J/hr/m^2$	$BTU/ft^2/hr$	0.0000881
$J/hr/m^3$	$BTU/ft^3/hr$	0.0000269
W	BTU/hr	3.414
W	J/hr	0.000278
W/m	BTU/ft/hr	1.041
W/m^2	$BTU/ft^2/hr$	0.317
W/m^3	$BTU/ft^3/hr$	0.0967
Pa	psia	0.000145
Pa	$"H_2O$	0.004014
Kelvin	Fahrenheit	F = 1.8K-460
Celsius	Fahrenheit	F = 1.8C+32
Fahrenheit	Rankine	R = F+460
Kelvin	Rankine	R = 1.8K

FOR TYPICAL COAL FUEL

ng/J	ppm @ 3% O_2 (SO_2)	1.18
ng/J	ppm @ 3% O_2 (SO_3)	0.941
ng/J	ppm @ 3% O_2 (NO)	2.51
ng/J	ppm @ 3% O_2 (NO_2)	1.64
ng/J	ppm @ 3% O_2 (CO)	2.69
ng/J	ppm @ 3% O_2 (CH_4)	4.69
ng/J	g/kg of fuel	0.000233

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APPENDIX C

SI PREFIXES

Multiplication Factor	Prefix	SI Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto*	h
10^{1}	deka*	da
10^{-1}	deci*	d
10^{-2}	centi*	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

*Not recommended but occasionally used

APPENDIX D

EMISSION UNITS CONVERSION FACTORS FOR TYPICAL COAL FUEL (HV = 13,320 BTU/LB)

To Obtain \ Multiply By	% Weight in Fuel		lbs/10^6Btu		grams/10^6Cal		PPM (Dry @ 3% O_2)		Grains/SCF. (Dry @ 12% CO_2)	
	S	N	SO_2	NO_2	SO_2	NO_2	SOx	NOx	SO_2	NO_2
% Weight In Fuel — S	1		0.666		0.370		13.2×10^{-4}		1.48	
% Weight In Fuel — N		1		0.405		0.225		5.76×10^{-4}		.903
lbs/10^6Btu — SO_2	1.50		1		(.556)		19.8×10^{-4}		(2.23)	
lbs/10^6Btu — NO_2		2.47				(.556)		14.2×10^{-4}		(2.23)
grams/10^6Cal — SO_2	2.70		(1.8)		1		35.6×10^{-4}		(4.01)	
grams/10^6Cal — NO_2		4.44		(1.8)				25.6×10^{-4}		(4.01)
PPM (Dry @ 3% O_2) — SOx	758		505		281		1		1127	
PPM (Dry @ 3% O_2) — NOx		1736		704		391				1566
Grains/SCF (Dry @ 12% CO_2) — SO_2	.676		(.448)		(.249)		8.87×10^{-4}		1	
Grains/SCF (Dry @ 12% CO_2) — NO_2		1.11		(.448)		(.249)		6.39×10^{-4}		

NOTE: 1. Values in parenthesis can be used for all flue gas constituents such as oxides of carbon, oxides of nitrogen, oxides of sulfur, hydrocarbons, particulates, etc.
2. Standard reference temperature of 530°R was used.

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